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THE IRON ORE DEPOSITS AT CORNWALL, PENNSYLVANIA.[1]

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OUTLINE.

THE Cornwall deposits occur in Cambrian limestone and dolomite along the southern border of a thick diabase dike. The ore was formed through the replacement of the limestone and dolomite by material carried in hot emanations from the diabase. The carbonate rocks have been altered to calcium-magnesium silicates and iron oxides. Sulphides of iron and copper are also present and are recovered as by-products in the concentration of the ore. The common minerals of the deposits are zonally arranged in relation to the diabase. It is concluded that the hot emanations came from the diabase adjacent to the ore bodies and that in general material

[1] Abstract of part of a dissertation entitled The Cornwall Ore Deposits, Pennsylvania, presented to the faculty of the Graduate School of Yale University in candidacy for the degree of Doctor of Philosophy.

was precipitated from them in the order silica, potash, iron, sulphur, and copper.

INTRODUCTION.

The Cornwall ore deposits are located about five miles south of Lebanon in the range of hills forming the southern boundary of the Lebanon Valley, a part of the Great (Kittatinny) Valley of Pennsylvania. Mining began at the deposits in 1742, when only a few thousand tons of ore were produced. The production has gradually increased until in the last few years it has reached more than 1,000,000 tons annually. In the early days of mining both iron and copper ores were extracted but the rich copper veins were soon exhausted and the deposits were worked for iron ore alone. The iron ore has always contained a small amount of disseminated copper, and in recent years, with the installation of ore concentration processes, copper in the form of chalcopyrite has again become a product of the mine.

The writer first visited the deposit late in December, 1928, from which time study was carried on at intervals until the summer of 1930, when three months of continuous field work was undertaken. The following winter an additional month of field study was added and several months devoted to laboratory and microscopic examination of specimens and to study of the literature.

The writer wishes to acknowledge his indebtedness to Professor Alan M. Bateman, under whose direction the work was undertaken. He also wishes to thank Professor Adolph Knopf for his aid in the study of the petrology of the diabase, also Professor Chester R. Longwell and Mr. George W. Stose. The writer's thanks are also due to the engineers at the Cornwall mines, especially Mr. Peterson, Mr. Barnhart and Mr. Moyer, and to the Bethlehem Mines Corporation for permission to publish this report.

GENERAL GEOLOGY.

The sedimentary rocks in the Cornwall district can be divided into two major groups: the folded early Paleozoic sediments and the unfolded Newark series of Triassic age. The latter lie unconformably upon the former and both have been intruded by late Triassic diabase.

An area of approximately 150 square miles about the ore deposits was mapped (Fig. 1) and the following stratiographic section was determined:

Triassic system
- Newark series
  - Gettysburg shale
  - New Oxford formation

—unconformity—

Ordovician system
- Martinsburg shale
- Leesport limestone

—unconformity—

- Stones River limestone
- Beekmantown limestone

Cambrian system
- Conococheague limestone
- Elbrook limestone

The only igneous rock of the district is diabase, which is intrusive into all the above-mentioned formations. A complete description of it follows in a later section.

The Gettysburg shale together with the New Oxford formation extend across the Cornwall district from the middle of the eastern side to the southwestern corner. The belt is about 4 miles wide east of the ore deposits at Cornwall, but is 8 miles wide near the western border of the district. The northern half of the belt is occupied by the Gettysburg shale and the southern by the New Oxford formation. Estimates of the thickness of the two formations vary considerably but that of Stose and Jonas [2] for the Lancaster quadrangle is: Gettysburg shale, 4500 feet; New Oxford formation, 4500 feet.

The Gettysburg shale consists predominantly of red shale interbedded with soft red sandstone. Lenses of limestone conglomerate are found in places along the northern border, and a basal fanglomerate (a hard quartzitic conglomerate) occurs in the eastern part of the area. The New Oxford formation con-

[2] Stose, G. W., and Jonas, A. I.: Geology and Mineral Resources of the Lancaster Quadrangle. Penna. Geol. Surv., 4th Series, Atlas no. 168, 1930.

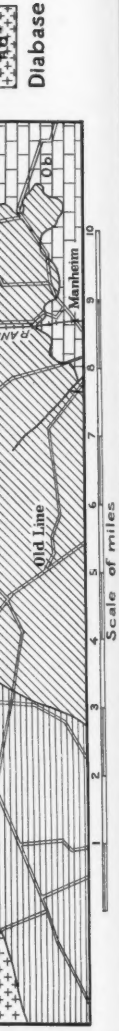
LEGEND
Ogg
Gettysburg shale
Onc
New Oxford formation
Unconformity
Om
Martinsburg shale
Ob
Beekmantown limestone
Cc
Conococheague limestone
Od
Diabase
Annville
Iona
Campbellstown
Fonlana
Mt Pleasant
Bismark
Cornwall
Mt Gretna
Lebanon
Hill Church
Upper Lawn
Lawn
Bellair
Mastersonville
Old Line
Mount Hope
Elsinore
White Oak
Penryn
Manheim
CORNWALL AND LEBANON RAILROAD
LEBANON & LANCASTER R.R. CO
Scale of miles

sists of alternate beds of yellow arkosic sandstone, red sandy shale, and soft red sandstone. The Gettysburg shale is considered the equivalent of the Brunswick shale of New Jersey, and the New Oxford formation, of the Stockton.

The distribution and area of the Martinsburg or Cocalico shale are shown in Fig. 1. Estimates of the thickness of the formation vary from 1000 to 3000 feet. It consists of a gray-black shale which weathers buff, interbedded with lenses of soft grayish brown sandstone and impure limestone. Folding at the time of the Appalachian revolution has crumpled it intensively, in places changing it to slate. The age has been determined as Upper Ordovician.

The Leesport limestone outcrops in a narrow band along the southern border of the Martinsburg in the northwest corner of the area but is lacking in the southern part. The Leesport is an extremely thin impure limestone, grayish in color. It is better developed in the Lehigh district, where it is called the Jacksonburg cement rock. It is of little importance in the Cornwall district.

An angular unconformity separates the Leesport limestone from the underlying limestones, which will be discussed in one group because of their similarity to each other. From the top downward they are the Stones River, Beekmantown, Conococheague and Elbrook limestones. All four are exposed in the lowland lying north of the Triassic belt with the oldest on the southeast and the youngest on the northwest. In addition, the Beekmantown is exposed in the southeast corner of the district. The total thickness for the Cornwall district is estimated as 4500 feet, divided as follows: Stones River 250 + feet, Beekmantown 2000 feet, Conococheague 2000 feet, Elbrook 250 + feet. The upper part of the Stones River and the lower part of the Elbrook are not exposed and so are not included in the above estimate. The Stones River contains the only pure limestone of the group. It is a dark blue-gray massive rock. The Beekmantown contains beds of light and dark blue low-magnesian limestone and light gray glistening dolomite. The top of the Conococheague formed of shaly impure limestone and limy shale under which lie beds of



alternate limestone and dolomite. It contains cryptozoon reefs at many horizons and a few beds of white sugary marble. The Elbrook contains light gray limestone and dolomite and some dark gray dolomite.

As the ore bodies were formed by replacement of the Conococheague limestone, some analyses of it are shown in Table I.

TABLE I.

ANALYSES OF CONOCOCHEAGUE LIMESTONE.[3]

	A.	*B.*	*C.*	*D.*	*E.*	*F.*	*G.*
$CaCO_3$	53.77	52.36	47.66	50.49	51.73	73.20	59.06
$MgCO_3$	42.92	41.74	42.26	41.04	45.35	11.60	30.50
SiO_2	1.68	4.95	6.94	5.67	1.20	8.32	7.42
$Al_2O_3 + Fe_2O_3$	1.10	.73	3.00	1.89	1.31	6.93	3.79

	H.	*I.*	*J.*	*K.*	*L.*	*M.*
$CaCO_3$	41.93	66.70	78.13	80.68	82.20	81.76
$MgCO_3$	21.16	21.19	8.37	10.12	3.96	6.58
SiO_2	11.20*	8.10	8.70	5.77	10.10	7.28
Al_2O_3	25.40*	4.12	1.94	2.13	1.58	1.97
Fe_2O_3			2.20	1.96	1.65	1.73

* Probably highly argillaceous and impure limestone from the top of the Conococheague formation.

A. Conococheague limestone, Easton, Pa., analysis by P. Skinner.
B. Conococheague limestone, Freemansburg, Pa., analysis by Beth. Steel Co.
C. Conococheague limestone, Hellerstown, Pa., analysis by Beth. Steel Co.
D. Conococheague limestone, Freemansburg, Pa., analysis by Beth. Steel Co.
E. Allentown (Conococheague) limestone, Allentown, Pa., analysis by Beth. Steel Co.
F. Conocheague limestone, north of Cornwall, Pa., analysis by Beth. Steel Co.
G., *H.*, *I.* Drill samples of Conococheague limestone, south side west end open pit mine, Cornwall, Pa., analysis by Beth. Steel Co.
J., *K.*, *L.*, M. Conococheague limestone, south side Middle hill Cornwall mine, Cornwall, Pa., analysis by Beth. Steel Co.

[3] Miller, B. L.: Limestones of Pennsylvania. Penna. Geol. Surv. 4th series, Bulletin M–7, 1925.

PETROLOGY OF THE DIABASE.

Distribution.—The Triassic diabase intrusives are confined to the belt of Triassic sedimentary rocks and to the limestone along the borders of the belt (Fig. 1). The diabase forms both concordant and discordant bodies. The concordant bodies cross-cut the sedimentary rocks to a slight extent but are generally inclined less than 15° to the bedding. The discordant bodies are inclined at much greater angles and in exceptional cases are perpendicular to the bedding.

In the eastern half of the Cornwall district the larger northern igneous body is an east-west trending dike, whereas the smaller southern one is a sill. The sill and dike at Cornwall are joined not far below the surface, whereas to the east and west the outcrop of the sill swings north to meet that of the dike, bringing the junction of the two to the surface in both places. Near the eastern border of the district the dike and sill both disappear, and, although there may be faulting along the eastern border of the diabase outcrop, no decisive evidence of it could be found. On the other hand, west of Cornwall where the intersection of the dike and sill are exposed, the evidence of faulting is decisive and two faults can be seen offsetting the diabase bodies. West of the faults the diabase outcrop separates into two parts; the northern extends westward and the southern southwestward. Stose and Jonas [4] state that the southern body is a sill dipping 30° NW. at Lawn. The northern body appears to be a dike dipping south, but the outcrops of its contacts are so obscured that no dips were obtainable and its character had to be inferred from offsets by faults.

Jointing and Fissuring.—Several joint systems occur in the diabase, but none of them are persistent. They are seen best in the mines at Cornwall. In the extreme border facies of the diabase, on the north face of the open pit where the contact is widely exposed, there is a rough columnar jointing perpendicular to the contact, which penetrates from six inches to two feet into the dike. At greater distances within the diabase regular joint sys-

[4] Stose, G. W., and Jonas, A. I.: *op. cit.*, p. 53.

tems were observed. They vary from two to three in number and each system is composed of many parallel joints, but none have a constant direction. At one place in the eastern ore body the jointing is so abundant that the diabase is almost a breccia. In this place either there are so many systems present or they are so irregular that it was impossible to determine their directions.

In a few places one system of joints became sufficiently enlarged to permit intrusion of diabase pegmatite or diabase aplite. In one case an aplite dike was traced across several drifts in the mine for a distance of several hundred feet. Another type of fissuring has taken place in which minute cracks now completely healed were invaded by mineralizing solutions. The relation of these cracks to the jointing was not determined.

Normal Diabase.—Rock of this type forms nearly all the diabase in the district; the other types are interesting only because of their genetic significance.

The normal diabase can be divided into a number of facies on the basis of textural changes. As each type of texture grades into the next, forming a continuous series, a division into various facies must be arbitrary. The writer has divided them as follows: glassy contact facies, crystalline contact facies, intermediate facies, and coarse facies.

The glassy contact facies, as its names implies, is composed mostly of basalt glass. Several thin sections made from the exact contact of the dike with the country rock, show the chilled border to be composed of 20 per cent. phenocrysts and 80 per cent. glass. The pure glass zone is seldom more than 5 mm. thick and at its inner edge microlites of feldspar (plagioclase?) begin to appear. The microlite zone may be up to 2 cm. in width. The glassy contact facies includes the microlite zone as well as that of pure glass.

The crystalline contact facies grades directly from the microlite zone and appears at the point where pyroxene becomes recognizable. The texture of this zone is still porphyritic, but the number of phenocrysts has decreased and only those of olivine are

recognizable. The groundmass has taken on a texture that is either ophitic or intersertal, depending on the relative proportions of plagioclase and pyroxene. This facies varies in width from 5 to 10 feet.

In the intermediate facies phenocrysts have disappeared entirely and the crystallization has become fairly coarse. The texture is ophitic to intersertal just as in the groundmass of the preceding facies. Orthoclase feldspar can be recognized filling the residual spaces between the plagioclase-pyroxene aggregates. The potassium feldspar is probably also present in the preceding facies, but was not recognized.

In the coarse facies the rock tends to take on a hypidiomorphic fabric, but traces of the ophitic still remain. The plagioclase laths become quite thick and penetrate the pyroxene grains. This facies is also characterized by the presence of micropegmatite and large irregular grains of late crystallizing iron ore.

The feldspars are of two kinds: plagioclase whose extinction angles indicate that it is labradorite, and orthoclase. The plagioclase was identified in all the facies and was found to vary within the limits of labradorite in specimens from the crystalline contact and the intermediate facies. In the coarse facies the plagioclase was determined more accurately because of the size of the individual grains. Several beautifully zoned grains were found on which it was possible to determine the composition of the zones. The inner zone is a bytownite ranging in composition from An_{71} to An_{74}. This inner zone grades outward to a zone of andesine ranging between An_{43} and An_{50}. No plagioclase exceeding these limits was found in the normal diabase. Plagioclase was one of the first minerals to crystallize from the magma.

The orthoclase appears only in the two coarse-grained facies of the rock. It seldom shows any twinning and never any crystal outlines. It is one of the latest crystallizing minerals of the diabase and commonly combines with quartz to form micropegmatite. Whether the orthoclase becomes sanidine in the fine-grained facies could not be determined because of the small size of the grains. The orthoclase and plagioclase taken together are

nearly always equal to or slightly in excess of the femic minerals. The orthoclase varies between 5 per cent. and 30 per cent. of the total feldspar and averages about 20 per cent.

The pyroxenes occur in all the facies of the diabase except in the glassy contact. Attempts to determine them in the finer grained facies were not successful because no interference figures could be obtained. In the coarse facies, however, two distinct species were found; the most abundant is the enstatite-augite variety called by Winchell[5] pigeonite. This is a monoclinic pyroxene which has a very small 2V and seems to be intermediate between clinoenstatite and augite. The other pyroxene is the orthorhombic variety enstatite, which extinguishes under crossed nicols when parallel to the prismatic cleavage; it has a very large 2V, and is positive.

The pigeonite was commonly found to have 2V varying between 15° and 20°, but one or two grains gave a nearly uniaxial figure. The enstatite always has 2V greater than 80° and is positive. The writer was unable to find any ordinary augite in the thirty sections of coarse diabase examined. The relative amounts of the two pyroxenes are hard to determine, as they can be distinguished only when the grains are in certain orientations. There seems to be about four times as much pigeonite as enstatite. The enstatite has crystallized before the pigeonite and in some places seems to be contemporaneous with the plagioclase. The pigeonite is later than the plagioclase, but appears to be earlier than the other minerals. The pyroxenes commonly form about 40 per cent. of the rock.

Micropegmatite in the form of microscopic intergrowths of orthoclase and quartz, along with free quartz, is abundant. The quartz is commonly intergrown with orthoclase, but it does occur in separate grains; in two of such cases no orthoclase was found near the quartz, whereas micropegmatite was present, indicating more quartz than was necessary to form micropegmatite. On the other hand, in three specimens the association is of grains of quartz and orthoclase scattered through the rock with no

[5] Winchell, A. N.: Amer. Geol., vol. 26, p. 199, 1900.

micropegmatite. Quartz in one or another of the above forms occurs in all the specimens from the coarse facies but was not found in specimens of the other facies.

Iron ore occurs in all the specimens but in different forms in the different facies. In both of the contact facies it was found as a secondary mineral, either an alteration product of the phenocrysts or a replacement of the other minerals and the glass. Where secondary, it occurs as minute rounded grains around the periphery of the phenocrysts or scattered irregularly through the rock. It also occurs in all the crystalline rocks as a late crystallizing constituent. Some specimens containing abundant iron ore were polished for microscopic examination to determine the nature of the iron ore mineral. It was surprising to find that in nearly every case the mineral is ilmenite and not magnetite, as is generally assumed to be the case. Only two or three grains, in all the specimens of coarse-facies diabase examined, are magnetite. The iron ore varies in amount up to nearly 10 per cent. It is generally about 4 or 5 per cent.

Apatite occurs in the coarser types of diabase, in the form of slender prisms in orthoclase. It is seldom found in any of the early crystallizing minerals.

Although some of the biotite gives the appearance of being of primary origin, most of it seems to be an alteration product of pyroxene. The biotite is strongly pleochroic with its color changing from light amber to deep reddish-brown. If it is of primary origin, it has crystallized after most of the rock had solidified and is nearly contemporaneous with the iron ore, as each is seen fringing and replacing the other.

Phenocrysts occur in both the glassy and crystalline contact facies of the diabase. The glassy rock contains phenocrysts of monoclinic pyroxene and plagioclase as well as of olivine. The crystalline facies, however, shows only olivine phenocrysts.

The alteration of the normal diabase will be discussed later in the paper.

Two complete analyses (Table II) of the diabase at Cornwall

TABLE II.

ANALYSES OF DIABASE AT CORNWALL.

	Coarse Diabase		*Fine Diabase*	
	%.	Mol. no.	%.	Mol. no.
SiO_2	53.09	.885	53.88	.898
Al_2O_3	14.97	.147	14.33	.140
Fe_2O_3	6.13	.038	3.23	.020
FeO	4.47	.062	6.54	.091
MgO	6.50	.163	7.25	.181
CaO	11.24	.201	10.92	.195
Na_2O	2.10	.034	2.08	.034
K_2O	.69	.007	.96	.010
H_2O	.40	—	.23	—
TiO_2	.90	.011	1.09	.014
P_2O_5	.16	.001	.10	.001
MnO	—	—	.09	.001
Cr_2O_3	—	—	.06	.001
	100.65		100.76	

Norm.

Sal.	%	%
Quartz	9.54	6.48
Orthoclase	3.89	5.56
Albite	17.82	17.28
Anorthite	29.47	26.69
Fem.		
Diopside	20.09	21.48
Hypersthene	8.59	15.29
Magnetite	8.82	4.64
Ilmenite	1.67	2.13
Apatite	.34	.34

Classification.

III...4 4 4	III...4 4 4
Presodic koghose	Presodic koghose

were made by F. A. Genth,[6] one of the coarse facies of the diabase and the other of the fine-grained diabase that lies on the border line between the crystalline contact and the intermediate facies.

The coarse-grained diabase is shown by the norm to contain more quartz and iron ore than does the fine-grained diabase. This is also demonstrated by the microscopic study of thin sections of the rock. On the other hand, although the norm shows

[6] Genth, F. A.: Mineralogy of Pennsylvania. Second Penna. Geol. Surv. Report, BB, p. 222, 1875.

the fine-grained diabase to contain more orthoclase than is contained in the coarse, some of the potash contained in the sericite and biotite of the fine-grained rock is calculated as orthoclase in the norm.

The numerous analyses of normal Triassic diabase from New Jersey quoted by J. V. Lewis [7] all fall into the auvergnose or camptonose sections of the quantitative classification. Likewise, Shannon [8] has analysed the diabase from Goose Creek, Virginia, and finds that it lies on the dividing line between the camptonose and auvergnose sections. Cornwall diabase, however, falls into the koghose section and consequently differs from those mentioned above in containing a larger ratio of quartz to feldspar.

Diabase Pegmatite.—Three or four small dikes of pegmatite were discovered by the writer in the normal diabase at Cornwall. They are similar in appearance to the normal rock unless examined at close range, and so are easily overlooked. The best exposure is in the worked-out eastern end of the open pit. A dike varying from 4 to 6 inches wide was traced for 20 feet. Both ends disappear under debris and were not found farther along the exposure.

Megascopically the texture of the pegmatite is striking. There are long curving crystals of pyroxene in a groundmass of coarse-grained feldspar and micropegmatite.

Most abundant and striking of the minerals of the rock is a micropegmatitic intergrowth of quartz and orthoclase. It is the last crystallizing part of the rock and fills the interstices between the other minerals. Although no quartz was found outside this intergrowth, some orthoclase was, which, however, commonly grades into an area of micropegmatite. The two other minerals present in abundance are albite and monoclinic pyroxene. The albite is less abundant than orthoclase, and the two feldspars together with the quartz are about three times as abundant as the femic minerals. The pyroxene is intergrown with hornblende

[7] Lewis, J. V.: Petrography of the Newark Igneous Rocks of New Jersey. New Jersey Geol. Surv., Ann. Rept., pp. 99–167, 1907.

[8] Shannon, E. V.: Mineralogy and Petrology of the Intrusive Triassic Diabase at Goose Creek, Virginia. Proc. U. S. Nat. Mus., vol. 66, pp. 1–86, 1924.

which replaces it in a pseudomicropegmatitic structure. About 10 per cent. of ilmenite is also present, which in a few places is partially altered to titanite.

Aplitic Rocks.—One extensive dike and several segregations of this rock were found in the underground workings of the Cornwall mines. The segregations occur in the coarse facies of the diabase along a line that is probably the trace of a plane cutting the drift. They are elongated parallel to the plane and occur at intervals of 5 or 10 feet. These segregations have the bright pink appearance of the aplite at their centers, but grade outward into the normal diabase. The largest is about 2 feet long and 6 inches across.

The aplite dike was traced from a drift in the coarse facies of the diabase into fine-grained rock where it cuts one drift in the porphyritic border. Beyond this point it was followed up a raise to the diabase-ore contact where it ends by dividing into several parts. The dike varies in width from 6 to 18 inches.

The aplite is everywhere characterized by a pink color with or without minute green specks, and by its brittleness and the hollow sound it makes when struck with a hammer. Microscopically the texture is seen to be hypidiomorphic granular.

The rock is composed almost entirely of orthoclase, which varies from 75 per cent. to 90 per cent. of the whole. The other minerals are pyroxene (probably diopside), datolite, and chlorite. The chlorite replaces all the other minerals. The datolite seems to have replaced the diopside completely in a large part of the aplite but shows no sign of having replaced any other mineral. Every thin section of the aplite shows some datolite.

Internal Alteration of the Diabase.—The greater part of the normal diabase as well as the pegmatite and the aplite have been altered to some extent. This alteration will be discussed by mineral rather than by rock types. It is believed that the alteration was caused by the small part of the magma still liquid after nearly all the minerals had crystallized.

Feldspar shows two types of alteration. The first and most abundant is sericitic alteration which, in general, attacks the

orthoclase and plagioclase equally although in a few specimens plagioclase is more susceptible. It is most common in the coarse facies of the normal diabase. The feldspars in the pegmatite and the fine-grained diabase are progressively less attacked than those in the coarse facies. The other type of alteration of feldspar is to kaolin, and has taken place intensively in the aplite and rarely in the normal diabase.

The pyroxenes have also altered extensively. In the normal diabase the alteration has been uralitization, chloritization, and the change to diallage, also, some of the pyroxene has been altered to biotite or to hornblende. In the pegmatite, pyroxene was found changing to hornblende, but in the aplite no alteration was seen. The areas of pyroxene alteration commonly coincide with those in which feldspar has been altered, but isolated cases occur in which each alteration has taken place without the other.

The only other mineral that is altered is olivine which occurs in phenocrysts. It has changed largely into a mass of green chlorite fibers showing a radial arrangement, and into very minute magnetite specks grouped around the periphery of the phenocrysts. This mode of alteration is characteristic of the olivine, and its products are all that is left of at least 90 per cent. of the phenocrysts. The alteration of the phenocrysts may have taken place before the glass surrounding them solidified.

Veins and Seams in the Diabase.—Shannon,[9] in studying the Triassic diabase in Virginia, found several kinds of veinlets cutting the diabase, many of which have altered the country rock. The writer's work at Cornwall has disclosed many of the same vein types. Some are filled predominantly with diopside and are enclosed by bands of altered diabase. The pyroxenes were altered to a pale greenish diopside and the feldspar was sericitized, and some of the ilmenite became titanite.

Chlorite seams have produced the same alteration as the diopside veins, except that the iron ore of the diabase remains unaltered. Zeolite veins show alteration in the form of partial sericitization of the plagioclase and chloritization of the pyroxene.

[9] *Idem.*

Adularia veins are accompanied by alteration of pyroxene to uralite and some of the iron ore to titanite.

Besides the veins that show alteration there is one very common type that does not. That is a " diabantine varnish " which coats by far the largest part of all the joints in the diabase.

Some of the joints of the diabase near the eastern end of the ore deposits have two-inch openings and have become filled with hematite in the form of a red powder, which in turn is coated by free-growing calcite crystals. These cavities at present are filled with running water and the calcite is being dissolved. This type of cavity filling is confined to a zone about twenty feet wide in the diabase bordering the ore. It occurs with such regularity that when a drift cuts diabase showing it, ore is assumed to be near by. Rare cavity fillings in the diabase have also been found containing specularite, magnetite, fluorite, pyrite, apophylite, chlorite, chalcopyrite, fibrous amphibole, serpentine, calcite, and quartz. Few of these minerals were found together and the paragenesis was not worked out.

CONTACT METAMORPHISM.

The term contact metamorphism has had so many shades of meaning in the past that it seems best to state just what it embraces in this paper. It includes both endomorphism and exomorphism. Endomorphism includes all the changes that the solidified parts of the igneous intrusion have undergone during the escape of the volatile substances from the rest-magma. Exomorphism, on the other hand, includes the changes in the invaded rocks that have been caused either by the volatile exhalations of the magma or simply by the heating effect of the magma on the surrounding rocks.

Exomorphism is much more complex than endomorphism as it deals with changes in several types of rock, whereas the latter deals only with changes in one type. At Cornwall metamorphism has changed the character of the Mesozoic sediments extensively though seldom intensively. On the other hand, the change has been much more pronounced but of less extent where limestone and limy shales are concerned.

Endomorphism.—Endomorphic changes were thoroughly studied in the dike at Cornwall. The small vein and cavity fillings with alteration of the neighboring rock are in reality endomorphic effects, but it was thought best to discuss them with the differentiates of the magma and consider under this head the extensive alteration of the border of the dike. In places scattered irregularly along the contact, areas have been so intensely altered that only traces of the original texture of the diabase remain. The altered areas grade into others where the rock has remained completely unaltered except for the change in the olivine phenocrysts, which is always present (see above).

The endomorphic changes are largely mineralogical and only in a few places have they obliterated the texture. Most of the original mineral constituents of the rock have been altered. The feldspar for the most part has been changed to sericite, whereas the pyroxene has either broken down into chlorite-serpentine-magnetite aggregates, or has been altered to diopside or hornblende. Biotitization of the whole rock occurs in places, and extensive replacement by calcite was noted. Many of these changes have been mentioned above as occurring in the normal igneous sequence, and it is believed that here also they are a part of the normal sequence but have taken place on a much larger scale and when the rock was comparatively cool.

Exomorphism.—Wherever the Newark series has been invaded by the diabase bodies, marked changes have taken place in the sediments. The most extensive and notable alteration is the loss of the red color, so prominent in the Newark series, which has affected the red shales and sandstones indiscriminately. Also, the shales close to the intrusion have been recrystallized to hornfels. One specimen taken in the field for the chilled border facies of the diabase turned out on microscopic examination to be a hornfels indistinguishable from the diabase megascopically. It was found within a few feet of the border of the diabase. The sandstone, on the other hand has undergone cementation; the calcite or shale cement of the sand grains has been changed to quartz, specularite, or some other resistant mineral. Also,

segregations of lean iron ore in the form of magnetite and specularite were found. Whether the segregations represent addition of material or simply a local movement of the iron caused by circulating hot water could not be determined.

The lateral extent of these changes is considerable. In places the outcrop of bleached rock extends more than a mile from the igneous outcrop, and considering the dip of the intrusion, the actual distance is over 3,000 feet. Examination of the altered zones above and below a nearly horizonal igneous intrusion, forced the writer to the conclusion that the extent of the upper contact zone is little if any greater than that of the lower.

The size of the metamorphic aureoles at Cornwall appears greater than is usual with intrusions of this size. It could not be determined whether the size is actually greater or merely appears so because of the striking color change induced in the sedimentary rocks. The writer believes, however, that it actually is greater, and is the result of the great permeability of the rocks, which allowed the heat to be transferred long distances from the intrusion either by circulating ground water set in motion by the heat itself or by volatile matter escaping from the magma.

The only other rock formation with which the diabase intrusions come into contact is the Conococheague limestone in two areas along the northern border of the Triassic belt. The smaller one, located south of Mt. Pleasant, is about one mile long, whereas the larger one, extending from the Fontana-Mt. Gretna road nearly to the eastern border of the region, is eight miles long. In width the contact-metamorphic zones in the limestone are less extensive than those in the Mesozoic sediments.

The alteration of the limestone is different from that of the Mesozoic rocks, and easy to distinguish only near the diabase contact. The larger eastern aureole has been considered by previous workers to be a separate formation, the Mill Hill slates. The writer on his first visit to the area recognized that it is not a true slate but a hornfels which he thought was equivalent in part to the bottom of the Martinsburg shale and in part to the top of the Shenandoah limestone. Later, G. W. Stose informed him

that it should be correlated with the top of the Conococheague formation, which is shale in places. During the detailed regional study in the summer of 1930 this correlation was checked and found to be correct.

This band of metamorphosed rock was studied carefully at Cornwall, where it is exposed in many highway and railroad cuts. Another band of it occurs in the limestone outlier south of the diabase dike. At the latter point the alteration is much more intense and addition of material from the diabase predominates over the more widespread effects caused by the heat of the igneous body. As the addition of material is so intimately associated with the ore bodies, this phase of the metamorphism will be considered with the ore bodies; only the heat effects will be discussed here.

The predominant effect of heat on the shale and shaly limestone has been to harden them and give them a gray to yellow color in place of the original blue-black. In many places the bedding has been obliterated and a fractured and cracked massive hornfels has resulted; in other places the bedding still shows. Where nearly pure shale has been metamorphosed, the bedding no longer can be seen, but where a shaly limestone has been altered the bedding is still visible in the hornfels.

Microscopic study shows the massive hornfels to be composed predominantly of quartz and cordierite, with subordinate amounts of andalusite, biotite, sericite, and impurities, such as limonite and an amorphous black material. The limonite is secondary and a product of weathering. The limy hornfels is composed of diopside, calcite, dolomite, and in some places feldspar and epidote. Very small garnets are found in a few places.

THE ORE DEPOSITS.

Historical.—Ore was first extracted from the Cornwall deposits in 1742 and mining was carried on by the operators of the local furnaces on a small scale for over one hundred years. In 1864, in order to end the disputes and litigation between the many owners of the deposit, a company was formed which had

charge of all the mining operations. Thereafter systematic mining was undertaken and the production of ore was increased. In recent years an annual production of over 1,000,000 tons of ore has been attained and the total ore mined up to 1930 is estimated as about 35,000,000 tons.

Copper ore was formerly produced at Cornwall. Veins carrying rich supergene concentrations of copper minerals were located in the upper parts of the iron ore. The total production of copper ore is not known, but in the period from 1848–1885 more than 8000 tons of ore averaging 15 per cent. copper were mined. Soon after 1885 copper production ceased, and only began again recently when the installation of the concentrating plant made it possible to recover the copper that is disseminated throughout the iron ore bodies.

Extent and boundaries.—There are two ore bodies at Cornwall (Fig. 2). The larger deposit, lying on the west, is exposed on the surface and was the seat of the first mining; the smaller eastern body lies under a cover of metamorphosed shale and has only recently been discovered. The western body was originally 4500 feet long but mining has reduced its length to 3000 feet. The width varies between 200 and 600 feet. The body dips about 25° south and becomes narrower with increasing depth. The maximum depth is at the western end, where the ore pinches out 800 feet below the original surface. The eastern ore body is located half a mile east of the western body; it is similar in shape and attitude to the latter, but is slightly smaller.

The footwall of both deposits is formed by the diabase dike on the north. This boundary is irregular in detail since, for the most part, it follows the wavy and contorted upper surface of the diabase dike. In a few places it is separated from the dike by unreplaced limestone. The southern or hanging walls of both ore bodies are determined by the distance to which intense replacement by iron minerals has affected the limestone. As the limestone is formed of beds of varying composition, some of which are replaced at a greater distance from the diabase dike than others, the southern boundary of the deposit is extremely irregular at the places where the limestone strata are perpendicular

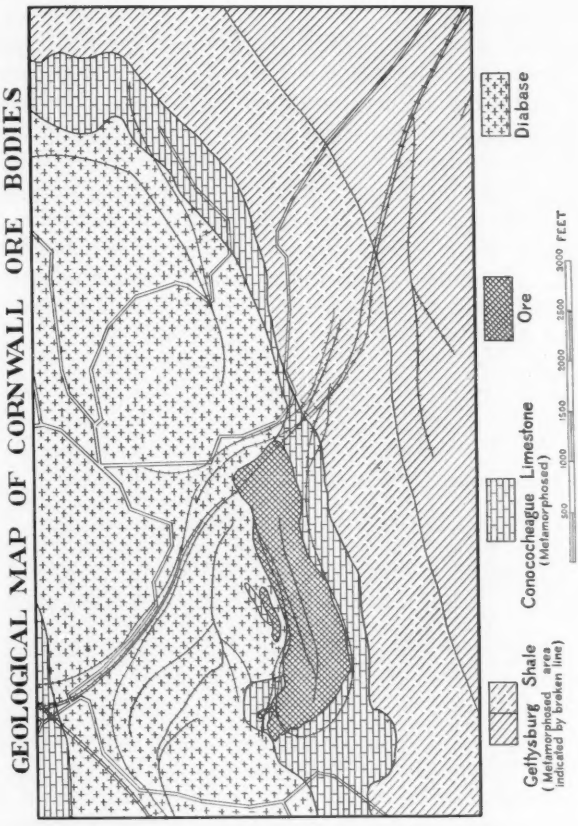

GEOLOGICAL MAP OF CORNWALL ORE BODIES
Gettysburg Shale
(Metamorphosed area indicated by broken line)
Conococheague Limestone
(Metamorphosed)
Ore
Diabase
500
1000
1500
2000
2500
3000 FEET

FIG. 2.

to the hanging wall, but fairly regular where the strata are parallel. The east, west, and lower boundaries of the deposits are wedge-shaped, due to the pinching out of the ore minerals in these directions.

Composition of Ore.—Before the Cornwall ore was concentrated it was sold in several grades according to the iron content, which varied between 62 per cent. and 30 per cent. The greater part of the ore, however, ranges between 35 per cent. and 50 per cent. iron, averaging in recent years about 40 per cent. Near the hanging wall the ore is higher in iron than near the foot wall, but in both places there is a wide range in iron content that can not be systematically ascribed to the position the ore occupies in the deposit. The diminution in iron content is accompanied by a corresponding rise in silicates, as can be seen from a comparison of the analyses [10] in Table III.

TABLE III.

PARTIAL ANALYSES OF CORNWALL ORE.
A. S. McCreath, Analyst.

	a.	*b.*	*c.*	*d.*	*e.*	*f.*	*g.*
Fe	65.0	57.0	51.5	49.0	46.5	42.0	39.0
SiO_2	4.0	8.5	12.5	13.0	18.0	21.0	20.0
$Al_2O_3 + CaO + MgO$	2.5	8.0	10.3	12.0	13.0	15.0	20.5

a. Nigger head ore, Middle Hill.
b. East face, Middle Hill.
c. West cut, north side, Middle Hill.
d. East face, Middle Hill.
e. Base of Middle Hill.
f. West cut, south face, Middle Hill.
g. East face, Middle Hill.

The analyses of Table IV are included to show the chemical composition of the ore at Cornwall and at some similar mines in Pennsylvania. They show in nearly all cases that the gangue is largely composed of calcium-magnesium-iron silicates. The rela-

[10] Leslie and d'Invilliers: The Cornwall Iron Mines. Second Penna. Geol. Surv., Ann. Rept. (1886), pt. 4, p. 533, 1887.

tive amounts of calcium and magnesium are variable, but the magnesium commonly predominates. This may be due to original differences in the limestones or to the greater mobility of the CaO than of the MgO, which has allowed some of the CaO to be carried off by emanations from the diabase.

TABLE IV.

ANALYSES OF IRON ORE FROM SEVERAL TRIASSIC DEPOSITS.[11]

A. S. McCreath, Analyst.

	a.	*b.*	*c.*	*d.*	*e.*	*f.*
Fe	51.05	46.40	41.90	42.75	39.60	34.55
Mn	.06	.24	.19	.52	.23	.21
Cu	.45	.07	.32	.37	.12	.17
Al_2O_3	1.39	7.82	4.97	1.82	5.90	4.33
CaO	2.74	2.55	2.81	5.32	1.90	10.09
MgO	3.94	2.74	7.46	4.31	11.38	7.96
S	2.53	.05	.43	.59	1.94	1.64
P	.01	.02	.02	.01	.06	.03
SiO_2	8.65	18.04	20.91	22.10	20.20	21.21
CO_2	?	?	?	—	3.50	.82

a. East face, Middle Hill, Cornwall, Pa.
b. Base, Big Hill, Cornwall, Pa.
c. South face, Middle Hill, Cornwall, Pa.
d. Underwood mine, Dillsburg, Pa.
e. Wheatfield mine, Berks County, Pa.
f. Phoenix mine, Boyertown, Pa.

Character of the Ore.—The chief characteristic of nearly all the ore from Cornwall is its banding, upon the basis of which several types of ore may be distinguished: (1) regular undeformed banded ore, (2) irregular contorted banded ore, (3) broken and jumbled banded ore, (4) unbanded ore. As each of these types can be traced from the ore to the adjacent limestone, they show that the ore and gangue minerals took their present position by replacing the limestone, since in no other way can sedimentary banding be preserved. The banding is obscure in the limestone; and under the microscope can be distinguished only by the amount of shaly material contained between the grains of calcite and

[11] Idem, pp. 532–537.

dolomite. However, when a specimen from near the ore-limestone contact is examined, a weathered surface shows the bands clearly, since weathering brings out color differences due to the slightly different mineral composition of the various bands after partial metamorphism. The shaly bands appear greenish, probably due to the weathering of small amounts of epidote, whereas the pure bands take on a gray color characteristic of the unmetamorphosed weathered limestone.

In the ore body itself the banding is even more clearly marked than in the adjacent limestone. There is no difficulty in distinguishing the bands even in fresh specimens since they contain different minerals. The shaly bands contain epidote, vesuvianite, and chlorite which give them a greenish tint, whereas the pure bands are composed of diopside, actinolite, talc, serpentine, and magnetite which give them a gray or black appearance. Such minerals as pyrite and chalcopyrite extend indiscriminately across individual bands. There is commonly a small amount of magnetite in the greenish bands but it is less conspicuous and less abundant than in the gray bands.

The greater part of the deposit is composed of undeformed banded ore which by its strike and dip shows that the original limestone was pressed into open folds before it was altered. This type of banding can be seen on a large scale at the eastern end of the open pit mine where the sediments were folded into a syncline on the north and an anticline on the south. The irregularly contorted and banded ore occurs in places where the beds have been crumpled during the folding of the limestone; it is not abundant and occurs only locally. The third type of banding is remarkable in appearance, as it gives to the ore the appearance of many small banded fragments piled together without order. There seem to be two explanations for this: one, that the original banded limestone was broken up while it was still soft at the time of formation; and the other, that a cave with banded limestone rubble in it was formed after the limestone had been uplifted and the overlying rocks eroded. A cave might easily have penetrated to this part of the limestone, since it appears probable that there was a Triassic erosion surface (marked by the unconformity be-

low the Triassic sandstone) within a few hundred feet of the mine. Both explanations may in part be true. The first is shown where a bed of broken pieces of rock now converted to ore can be seen extending for a long distance along the south side of the open pit. The second is also seen on the south side of the open pit, where a jumble of broken limestone fragments now converted into ore is found cutting across several beds of undeformed stratified material. In some places thick beds of unbanded ore are seen. Specimens from such beds appear homogeneous and although not abundant they are widely distributed. Beds of this type of ore have been followed across the ore-limestone boundary where they merge into unbanded limestone.

Mineralogy.

A microscopic study was made to determine the minerals present, their abundance and their distribution. The minerals may be divided into four groups: (1) ore minerals, (2) uncommon metallic minerals, (3) common gangue minerals, (4) uncommon gangue minerals.

Ore Minerals.—The ore minerals at Cornwall consist of magnetite with associated hematite, pyrite, and chalcopyrite. Records of early mining at Cornwall show that native copper, cuprite, azurite, malachite, covellite, chalcocite, and cobaltiferous wad were formerly extracted for ore.

Magnetite forms between 40 per cent. and 60 per cent. of the ore at Cornwall and shows considerable variation in abundance throughout the ore bodies. Commonly it occurs in euhedral crystals, rarely dodecahedrons, generally octahedrons, which range in size from 2 or 3 mm. in diameter to submicroscopic.

Microscopic examination shows that the magnetite crystals cut almost indiscriminately across grains of gangue. Where the gangue is composed of calcite and diopside, however, the magnetite shows preference for the calcite and as a result diopside grains may embay the edges of magnetite crystals or remain as inclusions in them. Likewise, where the gangue is composed of fibrous amphibole and diopside, the diopside may remain as inclusions within euhedral magnetite grains. The magnetite crys-

tals show no preferential action in any other type of gangue, such as combinations of diopside and phlogopite, actinolite and phlogopite, calcite and actinolite or any combination of the above-mentioned minerals with chlorite, but replace the gangue minerals completely and cut indiscriminately across mineral boundaries.

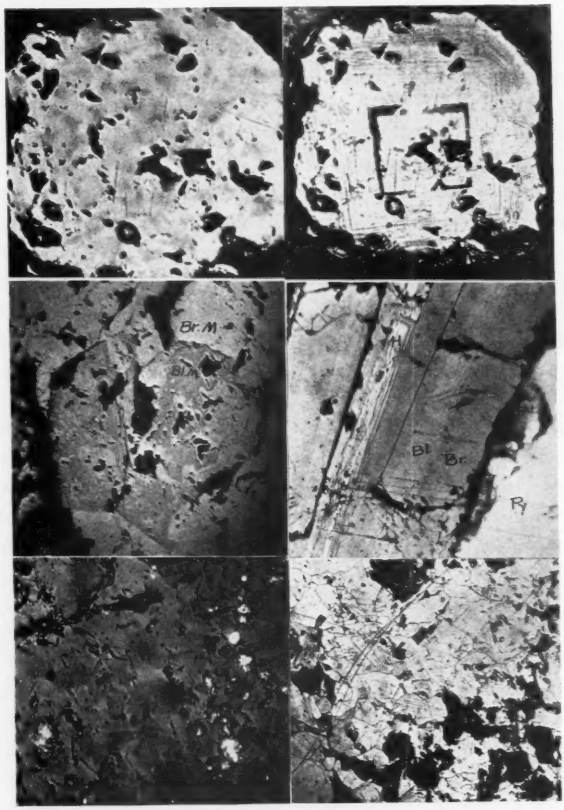
Magnetite is found in tabular crystals as well as octohedrons and dodecahedrons. This "platy" magnetite has long been known at Cornwall [12] and has been held to be magnetite pseudomorphic after hematite. However, L. L. Smith [13] finding the same material at French Creek, says: "This tabular structure (of magnetite) is clearly due to the replacement of the calcite along its cleavages which have formed directions of least resistance to the penetrating solutions."

Smith's explanation does not seem to fit the case, since residuals of unreplaced hematite were found in some of the tabular crystals, a strong indication that the magnetite received its present crystal shape from hematite. The "platy" magnetite occurs in two bands, a narrow discontinuous band along the footwalls and a thick continuous band along the hanging walls of both ore bodies. Since calcite occurs throughout the ore bodies and is not especially abundant in either of the bands, there is no reason why these bands occur where they do if Smith's explanation is correct. However, if the "platy" magnetite is pseudomorphous after hematite, the zonal arrangement of hematite in bands along the footwalls and hanging walls can readily be explained.

Several varieties of magnetite were encountered during the mineralographic study of the Cornwall ore. One type never previously reported is a very weakly anisotropic variety, the anisotropism of which is so weak that it can be seen only when adjacent grains have different optical orientations. There is no color change during the rotation of the microscope stage, but merely a lightening and darkening of the gray color of the grains (Figs. 7, 8). It could not be determined whether the anisotrop-

[12] Genth, F. A.: Mineralogy of Pennsylvania. Second Penna. Geol. Surv., Report B_2, p. 39, 1875.

[13] Smith, L. L.: Magnetite Deposit of French Creek. Fourth Penna. Geol. Surv., Bulletin, M–14, 1931.



FIGS. 3–8.

FIG. 3. Polished section of magnetite, single grain. × 70.

FIG. 4. Same as Fig. 3, etched with stannous chloride solution for two minutes.

FIG. 5. Brown magnetite (Br.M.) replacing blue magnetite (Bl.M.). × 145.

FIG. 6. Hematite (H) replaced by blue magnetite (Bl.), which is replaced by brown magnetite (Br.). × 145.

FIG. 7. Anisotropic magnetite. Crossed nicols. × 70.

FIG. 8. Anisotropic magnetite, etched 90 seconds, showing grain boundaries. Same specimen as Fig. 7.

ism is a temporary effect caused by distortion of the crystals under the force of the heavy blasts used at Cornwall, or the effect of some undetermined inversion of magnetite to a form of crystal symmetry lower than the isometric system. The areal distribution in the open pit suggests the former, as the anisotropic magnetite is found only in the deep parts which have recently been blasted. On the other hand, the fact that this type of magnetite is found in the underground workings where heavy blasts are not used and in places where there has been no recent blasting indicates that it may be due to some unknown inversion of magnetite, which disappears after exposure to weathering for some time. Whichever of the above explanations may be correct, it was proved by the writer that the anisotropism is not due to the change to ferromagnetic-ferric oxide or maghemite, as in one specimen both normal magnetite and maghemite show anisotropism and as analyses of several anisotropic specimens show that they contain considerable ferrous iron.

In addition to the anisotropic magnetite discussed above there are two other varieties of this mineral in the Cornwall ore deposits. Newhouse and Callahan [14] first noted their presence at Cornwall and described them as being very similar, but when seen together in the same specimen one is bluish and slightly harder than the other, which is brownish (Figs. 5 and 6). A second variety of magnetite was first discovered by Sosman and Posnjak [15] when they found they could oxidize magnetite until all the iron was in the ferric state without any loss of magnetism. In order to discover the molecular structure, Twenhofel [16] studied oxidized magnetite by X-ray methods, and at approximately the same time, Callahan and Newhouse were reporting its presence in many magnetic iron deposits and assuming the brownish variety to be ferromagnetic-ferric oxide. These papers were fol-

[14] Newhouse, W. H. and Callahan, W. H.: Two Kinds of Magnetite. ECON. GEOL., vol. 22, pp. 629–632, 1927. Also: The Ore Deposit at Cornwall, Pa. ECON. GEOL., vol. 24, pp. 403–411, 1929.

[15] Sosman, R. B., and Posnjak, E.: Ferromagnetic Ferric Oxide, Artificial and Natural. Jour. Wash. Acad. Sci., vol. 15, pp. 329–342, 1926.

[16] Twenhofel, L. H.: Changes in the Oxidation of Iron in Magnetite. ECON. GEOL., vol. 22, pp. 180–188, 1927.

lowed by communications, from Gruner [17] and from Wagner.[18] Wagner states that Schneiderhöhn has found the two kinds of magnetite in some South African ores collected by Wagner. Schneiderhöhn and Ramdohr [19] list the mineral maghemite corresponding to the previously discovered ferromagnetic-ferric oxide of Sosman and Posnjak, but they consider maghemite to be the bluish, harder variety, whereas the brownish, softer material is considered normal magnetite. This statement is contrary to the assumption of Newhouse and Callahan. None of the material at the writer's disposal was suitable for the separation of brown and blue magnetite and so no chemical analyses could be made.

The writer attempted to discover some etching test or other means of differentiating blue and brown magnetite when they do not occur together, but was unable to do so. It is, therefore, impossible to be sure to which variety the homogeneous magnetite specimens belong. However, etching of the two varieties with a saturated solution of stannous chloride in 20 per cent. hydrochloric acid always showed the brownish variety to be more strongly attacked than the bluish. As this solution does not attack hematite at all, it seems more probable that the bluish variety is the intermediate ferromagnetic-ferric oxide or maghemite. The difference in the speed of etching with the stannous chloride solution between different specimens of ore containing the brown and blue magnetite is greater than the difference in etching speeds of the two varieties themselves in any one specimen, and so etching speed can not be used to differentiate between the varieties when they are separate.

Textural relations between bluish and brownish magnetite show that at Cornwall the brownish variety is replacing the bluish. Fig. 5 shows the characteristic replacement structure in octahedral magnetite crystals, and Fig. 6 shows it in "platy" magnetite. On the basis of textural evidence, it is again uncertain whether the brownish or bluish variety is the normal magnetite.

[17] Gruner, J. W.: ECON. GEOL., vol. 22, pp. 744–749, 1927.

[18] Wagner, P. A., ECON. GEOL., vol. 22, pp. 845–846, 1927.

[19] Schneiderhöhn, H. and Ramdohr, P. Lehrbuch der Erzmikroskopie. G. Borntraeger, Berlin, 1931.

The evidence from the octahedral grains indicates that the bluish variety is normal magnetite and led Callahan and Newhouse to make their assumption. As, in this case, the brownish is replacing the bluish variety, it seems probable that the latter is the original magnetite that crystallized in octahedrons and so is the normal magnetite. If the brownish variety is normal magnetite, there must have been two changes, (1) oxidation completely changing the brownish magnetite to bluish followed by (2), a reduction that changes part of the bluish magnetite back to brownish. If any such sequence had taken place, it would be logical to expect a few specimens to show the bluish magnetite partially replacing the brownish, and as none were found it seems probable that the bluish magnetite is the variety that crystallized first in octahedrons and is therefore normal magnetite.

On the other hand, considering the relation between the two varieties of the "platy" magnetite, the brownish variety would seem to be the normal magnetite. This peculiar crystal form of magnetite has long been considered to have been original hematite changed to magnetite without loss of the original crystal outline. The hematite centers found in a few of the "plates" of magnetite are surrounded by bands of the bluish variety of magnetite which, in turn, are surrounded by the brownish variety. In the plates where hematite is no longer present, the centers are bluish magnetite and are surrounded by brownish. The bluish variety seems, therefore, to be transitional between hematite and brownish magnetite and to correspond with ferromagnetic-ferric oxide or maghemite.

Callahan and Newhouse thought that because the powdered ferromagnetic-ferric oxide is brown, it is more logical that it should be the brownish type of magnetite, whereas the bluish type should be the normal magnetite which has a black powder. This is not necessarily the case, as the colors of polished minerals seen through a reflecting microscope have little relation to the ordinary color of the mineral. Hematite, for example, although it crystallizes in red and black crystals and has a bright red powder, appears clear white under the reflecting microscope.

All the lines of evidence followed in trying to determine the

composition and relation between brownish and bluish magnetite led to contradictory conclusions, and no definite answer was reached. The final answer will have to be left until intergrowths of the two varieties are found which are sufficiently coarse to be separated and analysed, or until some method is discovered for differentiating between them when they do not occur together.

The *pyrite* at Cornwall is not only a source of iron and sulphur but also yields cobalt. During the concentration of the ore, pyrite is separated from the other minerals by flotation and is then burned to produce sulphur. The residue is chemically treated to extract the cobalt, after which the residual iron oxide is used as iron ore.

Pyrite occurs abundantly in the ore bodies at Cornwall. Although in places it forms 10–15 per cent. of the ore, it is commonly only 1–2 per cent. of the total. It is more abundant near the hanging wall of the deposit than near the foot wall, and in many places scattered crystals may be found in the limestone south of the ore bodies. The abundant pyrite in parts of the limestone is commonly connected with shatter zones and faults that might have acted as channelways to conduct some of the ore-forming solutions beyond the ore bodies.

The pyrite commonly occurs in euhedral crystals having combinations of cubic and octahedral forms. Some of the crystals become very complex with many additional faces.[20] The size of the crystals ranges from slightly less than a millimeter to well over a centimeter. Many aggregates of several individual crystals were found of considerably greater size.

The pyrite crystals disclosed in polished surfaces are mostly shattered, but some were found intact and these contain inclusions of minute euhedral magnetite grains and irregular to rounded diopside particles. The cracks in the fractured crystals are filled with calcite (dolomite), chlorite, serpentine, chalcopyrite, and sphalerite (in one specimen). Microchemical analysis of a normal pyrite crystal showed the presence of cobalt and, as no inclusions could be seen in the area analyzed, it was concluded that the

[20] Hawkins, A. C. and Frankenfield, J. S.: Pyrite from Cornwall, Pa. Amer. Min., vol. 13, pp. 252–253, 1926.

cobalt must be isomorphous with the iron in the pyrite molecular structure.

Chalcopyrite carries most of the copper occurring in the Cornwall deposits. Occasional analyses of the copper concentrates from the Cornwall ore show a greater amount of copper than chalcopyrite theoretically contains. It is thought that this may be due to the presence of small amounts of covellite and chalcocite in the concentrates, since some of the polished specimens disclose these minerals.

Chalcopyrite is distributed through the ore bodies fairly evenly, but increases slightly in concentration (with the pyrite) in the upper parts of the ore bodies and near their hanging walls. For the deposit as a whole the copper content averages about 0.25 per cent. with some places as rich as 1 per cent. or 2 per cent. Cu. In the upper parts of the ore bodies the copper may be concentrated along fracture lines forming discontinuous veins. In the early days of mining at Cornwall some of these veins were worked for copper, and due to secondary enrichment, the ore ran as high as 20 per cent. or 30 per cent. Cu.

Chalcopyrite commonly fills irregular cavities and cracks or occurs as a massive replacement about magnetite and pyrite crystals. All of it is polysynthetically twinned. Chalcopyrite was the latest of the common ore minerals to be deposited, since it fills cracks in the magnetite, "platy" magnetite, and pyrite.

Supergene enrichment of copper has taken place in the higher parts of the western ore body. Although the ore in this part of the open pit has been removed, remnants of copper veins can be found which yield specimens showing the carbonates and oxide of copper as well as normal sulphide enrichment. Secondary enriched copper ores are near the surface at Cornwall, due to the shallow water table and the narrow zone of oxidation. The eastern ore body shows no signs of enrichment and only the upper 50 feet of the western body shows it.

Uncommon Metallic Minerals.—Besides the ore minerals described above, many others were identified in the study of the ore deposits. Descriptions of them follow:

Sphalerite occurs, associated with chalcopyrite, in several veins cutting through the ore body. Commonly it is intimately intergrown with chalcopyrite, but in one case it was found replacing chalcopyrite along a small crack, thus indicating its age as latter than the chalcopyrite. Some sphalerite was seen in one specimen from the zone of supergene copper enrichment at the top of Big Hill.

One specimen containing *millerite* was found along the southern border of the western ore body. The millerite is distributed along a small crack cutting across a chalcopyrite vein and is distinctly later in age than the chalcopyrite. The specimen also contains sphalerite, but the age relationship between the millerite and the sphalerite could not be determined.

Chalcocite is a rare mineral at Cornwall, but occurs in some of the supergene copper ore; it is one of the supergene minerals. One specimen from deep in the ore body and far below the zone of supergene enrichment contains chalcocite thought to be of hypogene origin because of its position in the ore body.

Covellite is the common sulphide mineral of the enriched Cornwall ores. It also occurs sparsely in the deeper parts of the mine. where it may be of hypogene origin.

The two hydrous carbonates of copper, *azurite* and *malachite*, occur at Cornwall as stains and coatings around the former copper veins in the upper parts of the old mine workings. They belong in the oxidation zone of the deposits.

Cuprite was found by the writer along a mined-out copper vein on the top of Big Hill. Although no *native copper* was found, it has been reported associated with cuprite in the upper parts of the western ore body which are now removed.

Hematite was mentioned above in the discussion of magnetite, but since it also occurs unconnected with the magnetite it is considered here. Crystals of it occur in the hanging-wall limestone where they form a boxwork pattern, and also scaly aggregates fill cracks in the Triassic sandstone overlying the hanging-wall limestone. In both occurrences the hematite is the black variety specularite. It is useless for iron ore, at present, since it can not

be magnetically concentrated, but it has been used in the past when the ore was shipped without concentration.

Indeterminate hydrous iron oxides here referred to under the group name "*limonite*" are common in the Cornwall ore deposits as supergene minerals. They are commonly found as stains on rocks and minerals, but one specimen from the top of Big Hill shows "limonite" replacing pyrite.

Cobaltiferous crednerite and *rhodochrosite* were found by early investigators in the upper part (now removed) of the western ore body.[21]

The Gangue Minerals.—The gangue at Cornwall has commonly escaped close study since it is fine-grained and contains few minerals that assume distinctive crystal outlines. The dominant minerals, in order of decreasing abundance are: diopside, actinolite, phlogopite, chlorite, calcite, and dolomite.

Diopside is the most abundant gangue mineral in the Cornwall ores. It occurs throughout the deposits, but is abundant only in the part of the ore bodies lying just above the foot-wall. It is most abundant along the foot-wall and becomes less abundant on nearing the hanging wall, although a few specimens from the hanging wall contain 20 or 30 per cent. diopside. It occurs in nearly equidimensional grains without crystal boundaries; they are microscopic in size, never exceeding 0.5 mm. in their greatest dimension. Diopside seems to have been the earliest mineral to form in the Cornwall ores, with the possible exception of a small amount of feldspar (now largely altered to sericite). Diopside, in contrast to the other gangue minerals, shows considerable resistance to replacement by later minerals, especially magnetite. This resistance is thought to be the reason for the greater abundance of iron in the hanging wall part of the ore body where the proportion of diopside to actinolite is less.

Fibrous amphibole of variable composition occurs at Cornwall. The greater part is actinolite with a greenish color and faint

[21] Genth, F. A.: Mineralogy of Penna. Second Penna. Geol. Surv. Rept. B, p. 54 and p. 161, 1875.

pleochroism. In a few scattered areas the colorless fibrous amphibole tremolite is found; it is a member of the same solid solution series as actinolite but contains less iron. All of the fibrous amphibole will be called actinolite hereafter.

Actinolite is nearly as abundant in the ore deposit as diopside and its concentration varies inversely with the diopside content of the ore. It is more common near the hanging walls, but also occurs sparsely along the footwall. The individual crystals have a prismatic habit, forming slender needles up to 1 mm. in length. The needles have grown together to form a felt that is sharply cut across by the other minerals. In age, the actinolite is close to the diopside, possibly being a little later. It crystallized before the magnetite and phlogopite.

Phlogopite is abundant throughout the deposits. Although there are places in which the phlogopite is much more abundant than normally, no systematic arrangement could be determined for its distribution. The phlogopite grains are larger than those of diopside or actinolite, and may range in rare cases up to 10 or 15 mm. in their longest dimensions. They show partial crystal outline in thin section, commonly having two straight edges which are parallel to the basal cleavage.

The mineral is called phlogopite but may be in part biotite. Index determined for one specimen β or $\gamma = 1.584 - 1.585$.

Some of the phlogopite (labeled bleached biotite on the zonal distribution diagram) has been bleached colorless. This type is confined to a narrow strip along parts of the hanging wall. It differs from the normal green phlogopite in having no color or pleochroism; in all other respects it is similar to the normal mineral. The age relation of the phlogopite is difficult to determine but it appears to have crystallized after diopside and actinolite and before magnetite. Its time interval may in part overlap that of magnetite.

Chlorite is never absent but never abundant. The grains are small and irregular. In some places bands in the ore are nearly pure chlorite, whereas in others the chlorite seems merely to fill in around grains of other minerals or along cracks. It must have

formed throughout a long period of time and may even occur in two distinct generations. The chlorite of the bands is earlier than the magnetite, but that in cracks is later than the magnetite and the sulphides.

Some of the calcite and dolomite is later than the ore and accompanies the very last crystallizing minerals of the deposits, the zeolites.

Uncommon Gangue Minerals.—The calcium iron garnet, *andradite,* was found in several places in the ore bodies. Although never abundant and always in small crystals, it is distributed in patches in all parts of the deposits. In one spot near the western end of the western ore body a few large garnet crystals occur which have a maximum diameter of 2 or 3 cm.

Vesuvianite was found in one thin section. The specimen represents completely altered shaly limestone, which presumably supplied the alumina. The same specimen contains *fosterite.*

Epidote occurs in the contact-metamorphosed argillaceous bands of the limestone as small irregular grains that may be partially obscured by minute opaque impurities.

Adularia, the low temperature form of orthoclase, was found in several veins that cut the ore, and was noted in one footwall specimen on the highest mine level of the east ore body where it constitutes about 20 per cent. of the ore; it replaces argillaceous limestone. There are also some barren areas along the footwall of the west ore body that appear to have contained feldspar, of which nothing remains at present except sericite.

Albite occurs with diopside and actinolite in the higher levels of the eastern ore body. It is thought that the great abundance of the feldspar in the upper part of the east ore body may be due to the impurity of the limestone there, which supplied the alumina and part of the silica necessary for its formation.

Sericite is found as an alteration product wherever feldspar occurs in the ore bodies. In some places the sericitization has been so intense that the character of the original minerals can not be determined.

A mineral was observed in several specimens from the middle

of the open pit which is thought to be *brucite*, pseudomorphic after periclase. It has the optical properties of brucite and the crystal outlines of an isometric mineral.

Scapolite occurs sparsely in the limestone south of the western end of the open pit.

Tourmaline is found with the scapolite in the limestone south of the western ore body; it occurs in long thin needlelike crystals.

Fluorite (colorless) occurs in several places in the deposits but is more abundant, as a vein filling material, in the diabase adjoining the ore than in the ore bodies themselves.

Hornblende occurs sparsely in both ore bodies, but is abundant in a few specimens from the western part of the limestone hanging wall where it is associated with specular hematite.

Serpentine commonly occurs in veins that cut the ore. It is associated with talc, fibrous amphibole, chlorite, and phlogopite, being later in time of crystallization than all of them except the talc. A few specimens contain small amounts of serpentine that is not in veins but is a part of the ore itself.

Talc is less abundant than serpentine and is only found associated with it in the veins; it appears to have been contemporaneous with the serpentine.

Quartz veinlets were noticed in a very few thin sections of Cornwall ore. As the quartz is unaccompanied by any other mineral, its time of deposition could not be determined.

Datolite is abundant in one of the aplite dikes cutting the diabase footwall of the west ore body and also in the ore itself near the termination of this dike at the diabase-ore boundary. It is later in age than the normal ore and gangue minerals, with the exception of part of the chlorite with which it seems to have been contemporaneous.

Zeolites were observed in several microscopic veins, in thin sections of ore.

Zonal Distribution of the Abundant Minerals.—It seemed desirable to make a systematic study of the distribution of mineral concentrations in the Cornwall ore bodies. The only part of the deposits sufficiently well exposed to allow the necessary sampling

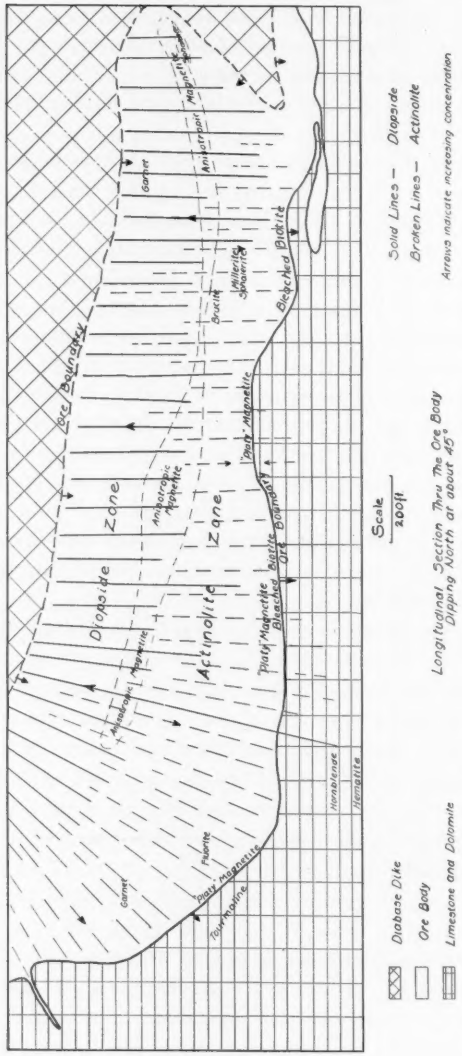


FIG. 9. Diagram showing zonal distribution of minerals.

is the open pit. Samples were taken at 100-foot intervals along east-west lines approximately 75 feet apart. Due to the 50° north dip of the south side of the open pit, the sampling gives a longitudinal section of the ore body that is roughly perpendicular to the footwall. After the specimens collected from the open pit had been examined microscopically, the data obtained from them were plotted and the zonal distribution diagram (Fig. 9) was drawn.

This diagram shows several distinct mineralogical zones, all of which appear to be related to the diabase dike lying below the footwall of the ore body. The diopside-actinolite distribution is striking in that the diopside always lies nearer the diabase than the actinolite, and although the two minerals overlap in places there is a regular decrease of diopside and increase of actinolite from a clearly marked diopside zone to an equally clearly marked actinolite zone. In addition, along the outer edge of the ore body there occurs a zone containing "platy" magnetite and in places bleached phlogopite or bleached biotite. Near the middle of the ore body is a longitudinal zone of anisotropic magnetite.

The conversion of limestone into silicate contact-metamorphic rock coincides almost exactly with the presence of abundant magnetite. In a few cases the silicates extend into the hanging wall of the ore body but never for a great distance. Likewise in a few cases the edge of the ore body as determined by magnetite content has penetrated into limestone that has been altered only by the addition of ore minerals without silicates. However, ore containing only calcite and dolomite gangue (unsilicified limestone) is as common in the center of the ore body as along the hanging wall.

The position of several minerals which are not abundant at Cornwall has been noted on the zonal distribution diagram although such occurrence can not be considered as marking a zone. No zones were determined for the brownish or bluish magnetite as no method could be determined for distinguishing them when they do not occur together.

Paragenesis

Feldspars
Diopside (Andradite, Feldspar, and Epidote)
Actinolite
Phlogopite
Chlorite
Hematite
Magnetite
Pyrite
Chalcopyrite
Sphalerite
Millerite
Calcite and Dolomite
Chlorite
Quartz
Serpentine
Talc
Brucite
Zeolites

Summary.—The outstanding features of the mineralogy at Cornwall are summarized as follows:

Magnetite, the chief ore mineral, occurs in three forms at Cornwall. The first is anisotropic and it is thought to be the result of some unknown inversion of magnetite to a crystal system of lower symmetry than the isometric. The other two varieties are normal isometric magnetite and maghemite or oxidized magnetite. Confusion in the literature as to whether the bluish or the brownish variety is normal magnetite is brought out and the difficulty of deciding the question from study of the Cornwall ore is explained. Proof is offered for the contention that "platy" magnetite receives its tabular form from hematite after which it is pseudomorphic, rather than by growth along cleavage planes in large calcite crystals. It is also suggested that the relatively richer iron ore in the actinolite zones along the hanging walls of the ore bodies may be due to the tendency shown by magnetite to replace actinolite more readily than diopside.

The pyrite at Cornwall carries about 1 per cent. cobalt. Specimens of pyrite that appear homogeneous when highly magnified

were found by means of microchemical tests to contain cobalt. Therefore, it is thought that cobalt replaces iron atoms in the pyrite crystal lattice.

Chalcopyrite carries nearly all the copper recovered from the Cornwall ore. It is more abundant along the hanging walls and upper parts of the ore bodies than in the lower parts. Near the top of the western ore body it was precipitated in discontinuous veins, which follow lines representing zones of weakness at the time the copper-bearing exhalations were coming from the diabase. Supergene enrichment of copper is noted in the upper part of the western ore body; the zone of enrichment is narrow and close to the surface due to a shallow ground-water table.

Diopside resists replacement by later minerals, whereas actinolite, phlogopite, calcite, and dolomite are readily replaced. Calcite and dolomite were formed in two generations, one antedating the intrusion of the diabase, the other late in the sequence of contact-metamorphic mineral formation.

Feldspar and epidote, both of which contain alumina, are in general restricted to the parts of the ore bodies which were formed from argillaceous limestone and dolomite. Minerals containing alumina are found only in the parts of the ore bodies where the invaded rock contains alumina.

The presence of several minerals containing elements classed as mineralizers is noted; they are scapolite, fluorite, datolite, and tourmaline, which contain chlorine, fluorine, and boron. These minerals are uncommon and occur in too small an amount to contain sufficient volatile elements to combine with and transport the iron of the ore body from the diabase into the limestone.

GENESIS OF THE ORE DEPOSITS.

Previous Theories.—A brief synopsis will be given of the many theories that have been advanced to explain the occurrence of copper and iron ores at Cornwall. These theories are readily divided into two groups: Those postulating a sedimentary origin and those setting forth an igneous origin.

All the early theories about the genesis of the Cornwall ore

deposits were based on a sedimentary origin. Rogers [22] stated his belief that the iron in the western ore body, which was the only one known at the time he wrote, was originally present in a shale that underlay the limestones of the Lebanon valley. The iron, he said, was changed *in situ* to the magnetic form by the heat from the diabase dikes, the dikes at the same time supplying the copper.

Leslie and d'Invilliers,[23] after extensive field study at Cornwall, came to many of the same conclusions as Rogers. However, they correctly placed the ore deposit in the Shenandoah limestone, but considered it to be at the top of the limestone, whereas, in reality, it is at the top of the Conococheague limestone and therefore in the middle of the Shenandoah. They believed that at the time of the intrusion of the diabase dikes, the limestone underwent alteration with the expulsion of much carbonate, and that consequently the iron already present was concentrated and recrystallized as magnetite and specularite. They called the hornfels above the ore bodies slate and thought it overlay the Shenandoah limestone. The slate, they said, formed a syncline running east-west, with the limestone emerging from under it to the north and south. The greater part of this supposed syncline has since been found to be coarse-grained diabase.

T. S. Hunt [24] and P. Frazer [25] have reported on the Cornwall mines, but as neither of them has added any new ideas to those stated above, a discussion of their papers will not be included.

Since 1909, when Spencer [26] first called on contact metamorphism to account for the ore deposits at Cornwall, no one has advanced a sedimentary theory of origin. The papers following

[22] Rogers, H. D.: The Geology of Penna. First Penna. Geol. Surv., vol. 2, pt. 2, p. 718, 1858.

[23] Leslie, J. P. and d'Invilliers, E. V.: The Cornwall Iron Mines. Second Penna. Geol. Surv. Ann. Rept. (1885), pp. 491–570, 1886.

[24] Hunt, T. S.: The Cornwall Iron Mine and Some Related Deposits in Penna. Trans. A. I. M. E., vol. 4, pp. 508–510, 1875.

[25] Frazer, P.: Report of Progress in York and Adams Counties. Second Penna. Geol. Surv. Rept. CC, p. 198, 1877.

[26] Spencer, A. C.: Magnetite Deposits of the Cornwall Type in Penna. U. S. Geol. Surv. Bull. 359, 1909.

Spencer's have differed only in details of the method of formation. Since Spencer's paper has brought about such a marked change in thought concerning these deposits, it merits an extensive discussion.

Spencer reasons as follows: the Cornwall ore body is a "chemical replacement of the limy rocks"[27] because (1) lean ore consists of alternate layers of iron minerals and unaltered rock, showing definitely that some portions are more favorable for replacement than others and (2) because many examples may be seen in which thin layers of ore, conforming to the stratification of the rock, are connected by cross seams which show that the ore minerals could not have been formed contemporaneously with the rock, but have been introduced subsequently. The iron forming the deposits is not an original constituent of the limestone that was metamorphosed, as can be seen from the character and analyses of the adjacent limestone, where the iron content is negligible and, therefore, the iron must have been introduced later, probably at the time the diabase was intruded.

The source of the iron and the water that forms the solutions that carry the iron are next considered, and by elimination the conclusion was reached that both originated within the diabase magma. Spencer favors the idea that the solutions carrying the iron arose from a deep magma chamber, either through the dike or along its borders, rather than coming from the adjacent cooling diabase, because all the deposits in Pennsylvania are related to discordant igneous bodies and not to concordant sills.[28]

Lindgren[29] discusses the magnetite deposits at Cornwall, but makes an erroneous statement, which can be traced to a paper by Callahan and Newhouse,[30] in calling the diabase intrusion at Cornwall a sill instead of a dike and the Paleozoic sediments calcareous shales when they are in reality argillaceous limestones (see analyses J. K. L. M. of these rocks in the section on General

[27] Spencer, A. C.: *op. cit.*, p. 13.

[28] Spencer, A. C.: *op. cit.*, p. 16.

[29] Lindgren, W.: Mineral Deposits, 3d ed., pp. 805–806. McGraw-Hill, 1928.

[30] Callahan, W. H. and Newhouse, W. H.: The Ore Deposit at Cornwall, Penna. ECON. GEOL., vol. 24, pp. 403–411, 1929.

Geology). The conclusions as to the origin of the deposit agree with those of the writer.

A recent paper by Callahan and Newhouse [31] reports the results of a mineralographic study of a small part of the western ore body. The zonal arrangement of the minerals of this part of the ore body is shown in a longitudinal section with results quite similar to those of the larger area sectioned for this report. Some structural details of the paper, however, are inaccurate, such as the accordance of the igneous body with the limestone, the presence of the Martinsburg shale above the ore body, and the constancy of the joint systems of the diabase dike.

Contact Metamorphism.

Contact metamorphism may be divided into: (1) extensive heating or baking effect on the surrounding rocks caused by the heat of the molten intrusive, (2) intensive metasomatic effect caused by exhalations of material from the magma as it solidifies. Neither of these processes goes on entirely by itself, and there is divergence of opinion as to whether there is a time interval between them. The heating process is nearly always accompanied by a slight giving off of exhalations, and the metasomatic process is accompanied by a rather high temperature, as is indicated by the nature of the minerals that crystallize from the exhalations (simple oxides and sulphides). Let us now see how these processes have taken place at Cornwall.

Recrystallization Due to Heat.—The heat from the diabase magma has affected the different rocks at Cornwall in varying degrees. The rocks most changed are the shales and highly argillaceous limestones at the top of the Conococheague formation. The shales have been recrystallized into a cordierite, andalusite hornfels, and the highly argillaceous limestones are altered with the formation of epidote and feldspar and possibly with a recrystallization of the calcite and dolomite. The limestone and argillaceous limestone beds underlying the shales and highly argillaceous limestones have altered less under the influence of heat.

[31] *Idem.*

Recrystallization of calcite and dolomite may have taken place but this could not be determined conclusively since all the thin sections of the Conococheague limestone specimens, whether collected near or far from the diabase intrusions, show the limestone to be completely crystalline and the grain size nearly equal in all the specimens. One specimen of a light colored bed of limestone occurring near the diabase contains calcite crystallized in tabular habit with the elongation parallel to the base; this unusual crystal shape may have arisen through recrystallization at the time of the diabase intrusion, but no proof of this could be found. The only sign of recrystallization seen in the thin sections is that the limestone distant from the intrusives contains rare grains of quartz, whereas that near the intrusions always contains a few grains of diopside presumably formed by recombination of silica, magnesia, and lime already in the limestone. (Compare silica content in analyses B, C, D, F, G, I, J, K, L, M.)

The assumption that slight metasomatism may have accompanied the recrystallization by heat is born out by the presence of areas altered to feldspar that have diverted the later exhalations around parts of the limestone. In several places along the diabase-ore contact areas were found, not only barren of magnetite and the other ore minerals, but also containing almost no silicates. Microscopic examination of specimens collected from these barren spots shows that the unaltered limestone is separated from the diabase by a zone 2 inches to 2 feet thick that is composed of feldspar, probably largely orthoclase but in part plagioclase, both of which have been changed almost completely to sericite. It is supposed that the feldspar formed an impermeable barrier, thus protecting the areas of unaltered limestone from the exhalations that elsewhere formed the ore bodies. If this is the case, the feldspar must have been formed before the diopside and later minerals were formed. Likewise, examination of the contact chilled diabase next to the feldspar zones bears this out in that it shows more intensive and deeper penetrating alteration, such as would be caused by the damming of the exhalations at the bound-

ary and their consequent spreading out through the border phase of the dike.

The character of the exhalations forming the feldspar dams seems to have been different from the later exhalations, in that the former must have contained alumina as well as soda, potash, and silica. It is believed that the exhalations of the main metasomatic period did not contain alumina, since all the minerals containing alumina which were formed in this period are localized in the shale bands of the limestone or in the highly argillaceous top of the Conococheague formation, all of which originally contained alumina. On the other hand, the feldspar, occurring in the feldspar zones of the barren areas, is not, in many cases, connected with shaly parts of the limestone, thereby making the transfer of alumina necessary for its formation.

Metasomatism—Time Relations.—After the maximum effect of heat had passed and the diabase magma had begun to cool and crystallize, the volatile matter which formed the Cornwall ore deposits was given off. It is believed that there is a break in time between the recrystallization of the surrounding rocks by the heat of an intrusion and the main outpouring of mineralizers.[32] The rocks were recrystallized at the time the magma was hottest, that is, when it had just been intruded and was almost completely liquid. On the other hand, the evidence indicates that the main outpouring of volatile matter took place after the border of the dike had completely solidified and the interior had partially crystallized. It can be seen that readjustment movements took place at this time which cracked and fissured the solidified border of the dike, because cracks and fissures, many of which have been cemented by minerals similar to those in the ore deposits, are abundant in the border of the dike, whereas the interior of the dike has suffered little fracturing and none of the interior fractures have been healed in this fashion.

The rest-magma of the diabase, which finally crystallized into

[32] Barrell, J.: U. S. Geol. Surv. Prof. Paper 57, 1907. Goldschmidt, V. M.: Die Contactmetamorphose im Kristianiagebeit. Kristiania, 1911. Umpleby, J. B.: U. S. Geol. Surv. Prof. Paper 97, 1917.

orthoclase, ilmenite, magnetite, and quartz, was rich in potash, iron oxides, and silica. These are the materials which were added to the limestone to form the ore deposits. As the rest-magma was under pressure due to the increase in volume caused by the crystallization of a large part of the originally molten rock,[33] it seems probable that when the cracking and fissuring of the chilled border of the diabase took place, the cracks formed outlets for the highly compressed, more volatile part of the rest-magma. Since the rest-magma existed only late in the solidification of the diabase, a considerable time interval must have elapsed between the recrystallization of the country rock and the period of metasomatic replacement of the limestone by the more volatile part of the rest-magma.

Damming of the Ore-forming Solutions.—Spencer [34] believes that the limy shale and the Mesozoic shale acted as an impermeable barrier to the mineralizing solutions given off by the diabase and confined them to the underlying limestone. The writer's work has confirmed this belief. It seems certain that a thick cover of rock lay over the Cornwall deposits at the time of their formation, not only because of the evidence of the slowly-cooled, coarse-grained diabase adjacent to the ore bodies, but also because of the erosional history of the region.[35] The area around Cornwall must have been deeply covered by rock until long after Triassic time in order that the Cretaceous (?) and later peneplanes and partial peneplanes could have been formed.

The rock cover must have consisted in part of the top of the Conococheague formation (shale), and in part of the Gettysburg shale. Since the ore-forming solutions have nowhere penetrated far into these shaly strata, it is logical to conclude that these shales were relatively impervious to the ore-forming solutions.

[33] Morey, G. W.: The Development of Pressure in Magmas as a Result of Crystallization. Jour. Wash. Acad. Sci., vol. 24, pp. 219–230, 1922. Ross, C. S.: Physico-chemical Factors Controlling Magmatic Differentiation and Vein Formation. Econ. Geol., vol. 23, p. 879, 1928.

[34] Spencer, A. C.: Magnetite Deposits of the Cornwall Type in Penna. U. S. Geol. Surv. Bull. 359, p. 21, 1909.

[35] Hickok, W. O.: Erosion Surfaces in South-Central Penna. Amer. Jour. Sci. (5) vol. 25, pp. 101–122, Feb., 1933.

Composition and Temperature of the Diabase Exhalations.— The minerals in the Cornwall ore deposits indicate that a considerable range in composition and temperature must have occurred in the solutions that carried the material forming the ore and gangue. High temperature minerals such as diopside, hematite, magnetite, and garnet occur along with the low-temperature hydrous silicates, serpentine and talc, and some of the zeolites. On the other hand, silicates, oxides, and sulphides are all represented in the ore deposits.

From a study of the paragenesis it can be established that material was precipitated from the exhalations of the diabase magma in the following order: potash, silica, iron oxides, sulphides of iron (with cobalt) and copper, hydrous silicates. The potash and silica are in part contemporaneous, for both started to deposit at the same time although the silica continued long after the deposition of potash had ceased. The iron oxides began to be deposited after the potash deposition had ceased but they slightly overlapped the silicates. Sulphur, with iron and cobalt, began to be precipitated at the close of the iron-oxide period and continued without cobalt and iron through a period of copper precipitation. Following the copper-sulphur period no great amount of material was added to the deposits, but a lengthy sequence of mineral precipitation took place, giving rise to the many low-temperature hydrous silicates. The amount of silica needed for the formation of hydrous silicates is so small that possibly it did not come from the rest-magma, but may have been dissolved from material along the channels followed by the hot waters still being given off by the magma and then reprecipitated at a place where the temperature of the solution had fallen.

At the time of the precipitation of copper a change was taking place in the mode of deposition. The hitherto large abundance of precipitating material gave place to small amounts which were deposited in scattered veins. The causes of the change may have been, (1) shrinkage of the volume of emanations, (2) dilution of the emanations so that they carried very little solid material in a large amount of water, or (3) a change from gaseous to liquid emanations, which followed fracture zones and did not permeate

the rock far from them. The first of these postulates undoubtedly took place, and it is the writer's opinion that the second also occurred.

Causes of Order of Mineral Precipitation.—The precipitation of the ore and gangue minerals in the order of paragenesis is the result of two different factors, first, changing composition of the emanations from the diabase rest-magma, and second, differential precipitation of minerals caused by changing temperature of the solutions.

The theory of differential precipitation with changing temperature brings in the concept of a definite emanation with a constant composition which, in travelling away from its source, is gradually cooled until its temperature is sufficiently low to cause the supersaturation and consequent precipitation of the different minerals in some order determined by the relative solubilities of the dissolved materials. It is impossible to apply this concept to the complete sequence of mineralization at Cornwall, but it is applicable to parts of the sequence. The areal distribution (Fig. 9) and precipitation time of diopside relative to actinolite may be explained in this manner. Likewise, the magnetite-chalcopyrite distribution may in part be thus explained, since chalcopyrite is relatively more concentrated than magnetite in the upper parts of the ore bodies, whither the emanations would have to move when they could not escape through the impervious Triassic barrier.

On the other hand, the preponderance of silicate precipitation in the early stages of mineralization can be explained only by different compositions of emanations emerging from the diabase. The increase in the concentration of magnetite along the hanging walls of the ore bodies over that along the footwalls is not sufficient to explain its precipitation later than the silicates as differential precipitation, because actinolite, which was formed before magnetite, has a more pronounced concentration away from the source than magnetite. This could not be the case if the magnetite were formed after actinolite from a solution, the temperature of which gradually diminished as it travelled farther from its source in the diabase. The best explanation of the increase in the hanging-wall concentration of magnetite seems to

lie in the fact that actinolite is more readily replaced by magnetite than is diopside, therefore magnetite is more abundant in the actinolite zones along the hanging walls.

The exhalations coming from the rest-magma of the diabase intrusive have been shown above to have changed their composition radically at least once during the sequence of mineralization at Cornwall. It might be argued that there was a break in the sequence of emanations at the time of the change of character, but this seems improbable, since the beginning of the hematite and magnetite precipitation coincides with, and in places slightly overlaps, the end of the precipitation of phlogopite and chlorite. A second change in the composition of the emanations probably took place after the precipitation of the copper and sulphur. This change is thought to be a minor one, marked chiefly by an abundance of water in the later emanations.

Transportation of Iron and Silica.—The greatest metasomatic effect at Cornwall is the introduction of silica and iron oxides into the limestone. The means of transporting iron and silica in solution has aroused considerable speculation in geological literature; recently some clarity has been achieved through the application of physico-chemical principles to ore-forming processes. Recent experiments by Morey [36] and the application of Morey's results to ore deposits by Ross [37] have shown that in hydrothermal and contact-metamorphic deposits large amounts of silica can be carried by water solutions at very high temperatures and pressures, if small amounts of potash are present. The presence of potash (and the mineralizers which are common in high-temperature ore deposits) will, under high pressures, raise the critical temperature of water so that it is possible to have water in the liquid state at temperatures of over 500° C.

A new field of experimentation and speculation is thus opened by raising the critical temperature of water. Ross [38] states that silica becomes abundantly soluble in water, if a little potash is

[36] Morey, G. W.: The Ternary System H_2O–K_2SiO_3–SiO_2. Jour. Amer. Chem. Soc., vol. 39, pp. 1173–1229, 1917.

[37] Ross, C. S.: *op. cit.*

[38] Ross, C. S.: *op. cit.*, p. 884.

added to keep the water liquid above the critical temperature. The movement of silica at Cornwall from the diabase rest-magma to the limestone as a concentrated aqueous solution can readily be explained, since potash was carried in the same solutions.

The transportation of the iron oxides is more difficult to explain. No experimental data for iron-oxide solubility at temperatures above the critical temperature of water are available, so no definite conclusions can be drawn. However, there is no reason to believe that the iron oxides are not as soluble as silica in water solutions at temperatures of 500° and 600°. Consequently the iron may have travelled as oxides from the dike to its position in the ore bodies. On the other hand, it has long been considered probable that the iron is carried in the form of soluble iron halides and changes to the oxide form only at the time of precipitation. This method of transportation not only offers a means of moving the iron but accounts for the larger ratio of ferric to ferrous iron in contact-metamorphic aureoles than in the igneous bodies around which the aureoles have formed, because since ferric chloride is more soluble than ferrous chloride, the ferric iron is more readily transported. Both chlorine and fluorine were present in the exhalations at Cornwall and were precipitated during the formation of the minerals scapolite, fluorite, and tourmaline, but these minerals occur in such small amounts that it is inconceivable that they contain sufficient halogens to combine with all the iron that was transported.

Although the theory of transportation of iron as oxides does not account for the change in the ratio of ferric to ferrous iron that takes place during transportation, another theory proposed independently by Butler [39] and Von Eckermann,[40] does. This theory states that the CO_2 set free by heat in a limestone contact-zone will react with ferrous oxide to form ferric oxide. Lasky [41]

[39] Butler, B. S.: Ferric Oxide Content of Limestone Contact Zones. Econ. Geol., vol. 18, p. 398, 1923.

[40] Von Eckermann, H.: The Rocks and Contact Minerals of Tennberg. Geol. For. Forhandl., vol. 45, p. 465, 1923.

[41] Lasky, S. G.: The Systems Iron Oxides: CO_2: CO, and Iron Oxides: H_2O: H_2, as applied to Limestone Contact Deposits. Econ. Geol., vol. 26, pp. 485–495, 1931.

has modified this concept in view of more recent physico-chemical evidence, and shows that Fe_3O_4 will be formed when FeO is oxidized and that a second molecule of CO_2 must react with Fe_3O_4 to produce Fe_2O_3 The second reaction, Lasky says, seldom takes place in nature because of the large preponderance of CO_2 over CO that is necessary to produce hematite from magnetite. Lasky concludes that although the reduction of CO_2 to CO probably accounts for the oxidation of FeO to Fe_3O_4, the presence of Fe_2O_3 must be accounted for by the greater volatility of $FeCl_3$ than of $FeCl_2$ and, therefore, all of the Fe_2O_3 in the contact deposits must have been transported in the form $FeCl_3$ and must have been precipitated directly from the chloride as hematite.

Without the supposition of a great loss of halogens into the surrounding rocks, there is an insufficient amount of chlorine and fluorine in the minerals at Cornwall to have combined with the iron necessary to form even the small part of the iron ore that was precipitated as hematite. As chlorine is not readily precipitated from hot aqueous solutions, the discrepancy between the amount of halogens present at Cornwall and the amount necessary to move the part of the iron that precipitated as hematite may possibly be explained by the escape of large amounts of chlorine into the surrounding rocks.

On the other hand, hematite is commonly found on the outer edges of the ore deposits. Since CO_2 is formed in the replacement of the carbonates by silicates, and since CO is formed only in the reduction of CO_2 to CO that occurs during the oxidation of FeO to Fe_3O_4 or Fe_3O_4 to Fe_2O_3, it seems probable that the presence of hematite along the borders of the ore bodies may be explained by the more complete oxidation of iron due to the smaller ratio of CO to CO_2 along the borders where less CO has been formed through oxidation of iron.

There is another form of Fe_2O_3 in the ore bodies that can not be explained by assuming that all the Fe_2O_3 was formed by precipitation directly from $FeCl_3$. This form is the maghemite (ferromagnetic-ferric oxide) which occurs, with magnetite, crystallized in octahedrons. Regardless of which form of the

magnetic iron oxides is the maghemite and which is the magnetite, oxidation of part of the material from Fe_3O_4 to Fe_2O_3 must have taken place. If the oxidation is hypogene in origin, which seems probable, the Fe_2O_3 in the maghemite must have been produced by means of some oxidizing agent such as CO_2 in the presence of small amounts of CO. If it is possible to oxidize part of the Fe_3O_4 to Fe_2O_3 after precipitation, which has undoubtedly taken place, there is no reason for assuming the Fe_3O_4 may not likewise be oxidized during or before precipitation, thus forming hematite.

Preferential Replacement of Certain Beds of Limestone by the Ore-forming Solutions.—It has long been known [42] that the more shaly beds of the carbonate rock at Cornwall contain a larger proportion of magnetite than the non-argillaceous beds. Callahan and Newhouse [43] assumed that these beds were more readily replaced by the ore-forming solutions on account of their shale content. The writer thinks that a more satisfactory explanation of the preferential replacement may be found in the association of a high magnesia content with the extensively replaced shaly beds.

Place of Origin of the Copper, Cobalt, and Iron.—No dispute has ever arisen over the place of origin of the copper and cobalt in the Cornwall deposits. Every investigator since the time of Rogers [44] agrees with him in assuming that the two metals came from the diabase magma. No such coincidence of theories exists in regard to the place of origin of the iron. Early investigators believed it occurred originally in the sedimentary rock, but time and more thorough investigation have disproved their theories, and it is now believed that the iron, also, has come from the diabase magma. Spencer [45] thinks the iron came from a deep-lying magma chamber and travelled upwards either through or along the borders of the cross-cutting offshoots of the magma body.

[42] Rogers, H. D.: First Penna. Geol. Surv., vol. 2 pt. 2, p. 718, 1858. D'Invilliers and Leslie: Second Penna. Geol. Surv. Ann. Rept. (1885), pp. 491–570, 1886. Spencer, A. C.: U. S. Geol. Surv. Bull. 359, 1909. Callahan and Newhouse: Econ. Geol., vol. 24, pp. 403–411, 1929.

[43] Callahan and Newhouse: *op. cit.*

[44] Rogers, H. D.: *op. cit.*

[45] Spencer, A. C.: *op. cit.*

Callahan and Newhouse,[46] on the other hand, believe that the adjacent solidifying diabase gave off the iron that formed the deposits. It is the writer's belief that the latter hypothesis is correct.

Not only are the ore and gangue minerals zonally arranged, indicating that the ore-forming solutions came directly out of the dike itself to the place of deposition, but also remnants of a rest-magma of suitable composition to form the ore deposits were found in the diabase adjacent to the ore body. Callahan and Newhouse have considered the conclusions that may be drawn from the zonal arrangement of the ore and gangue minerals. Such zonal arrangement, coupled with the presence of the same minerals along fissures in the border of the dike, makes almost certain the conclusion that ore-forming emanations came from the interior of the dike adjacent to the ore bodies, even if their point of origin was farther removed.

The course of differentiation in the solidifying magma has been traced (see section on Igneous Rocks) through several stages to water-rich differentiates capable of producing replacement similar to that in the ore bodies. It seems probable, therefore, that such local differentiation rather than some far distant source supplied the emanations. That such a large body of ore could have been formed by emanations from the near-by diabase will be disputed by some investigators, on the grounds that there is insufficient diabase near the ore bodies to produce sufficient material to form the ore. However, although the surface outcrop of the diabase is only 6 or 8 times as wide as the ore outcrop, the diabase widens with depth, as can be seen from the 30° south dip of the southern border of the dike and the perpendicular or northward dip of the northern border. On the other hand, the width of the ore body shrinks with depth, making the volume ratio of the diabase to the ore many times greater than 6 to 1.

It may also be argued that if the emanations came from the diabase adjacent to the ore they should be found everywhere along the diabase border, because if differentiation took place in one spot in the diabase, it should also have taken place elsewhere. How-

[46] Callahan and Newhouse: *op. cit.*

ever, other factors enter into the causes of ore formation besides the formation of a suitable rest-magma. There must be some method of collecting the residual liquid from among the network of early crystallized minerals in the diabase, such as filter pressing, and there must be some means for the water-rich solutions to escape through the solidified borders of the intrusive. Only in isolated places can it be expected that both of these factors will operate at the exact time that the diabase has crystallized sufficiently to produce a rest-magma suitable to form ore deposits. In addition to all the above conditions, there must be some rock capable of catching and precipitating the material carried by the emanations. When the above conditions are born in mind it seems more remarkable that there are any places where ore is formed along an igneous contact than that it does not form along the whole extent of the contact.

As there is no reason to suppose that the adjacent diabase is incapable of supplying enough material, it seems logical to conclude that the source of the ore-forming materials is in the diabase adjacent to the ore bodies, especially since it has been demonstrated that the diabase during its solidification produced water-rich differentiates capable of forming the ore.

COMPARISON WITH OTHER METAMORPHIC DEPOSITS.

The acceptance of a contact-metamorphic origin for the ore deposits at Cornwall was delayed for many years because it was thought that the striking mineralization that commonly accompanies such deposits was lacking. However, this is not the case, since mineralization at Cornwall is strikingly similar to that at other contact-metamorphic deposits, differing only in the absence of a few minerals from Cornwall and in the position of the contact-metamorphic aureole in relation to the ore, as will be shown later.

Several deposits besides those at Cornwall lack visual mineralogical evidence of a contact-metamorphic origin, but nevertheless were formed in that way. Ransome [47] says of the de-

[47] Ransome, F. L.: U. S. Geol. Surv. Prof. Paper 21, 1904.

posits at Bisbee, Arizona: " In a preliminary sketch of the Bisbee copper deposits published before any microscopic study had been made of the ore and country rock, it was stated that little or no contact metamorphism had affected the limestone. Closer study has shown that the metamorphism is much greater than mere field examination indicated."

The same is true of the Cornwall deposits. The widespread effect of contact metamorphism on the early Paleozoic limestone at Cornwall is seen only by microscopic study of ore and gangue specimens. The contact-metamorphic silicate aureole coincides in extent with the ore, and the silicate minerals, being fine-grained, are commonly overlooked in the field.

Contrast of Mineralogy.—A study was made of the mineralogy of the aureoles of twenty contact-metamorphic deposits: *iron*—French Creek, Pa., Hanover, N. M., Shasta Co., Cal., Iron Springs, Utah, Taylor Peak, Colo., Vancouver Island, B. C., Whitepine, Colo.; *copper*—Bisbee, Ariz., Clifton-Morenci, Ariz., Kasaan Peninsula, Alaska, Mackay district, Idaho, Pima Co., Ariz., Prince of Wales Island, Alaska, San Francisco, Utah, Yerington, Nev.; *tin*—Seward Peninsula, Alaska, York, Alaska; *tungsten*—Inyo Co., Cal.; *lead*—Darwin, Cal., Cooke City, Montana. Table V shows the mineralogical differences between Cornwall and other deposits that have a similar origin.

Reference to Table V shows that in the case of nearly every mineral the Cornwall deposits are similar to other contact-metamorphic deposits. There is only one striking exception (garnet) and a few minor exceptions (epidote and vesuvianite).

Fifteen out of the twenty deposits tabulated contain abundant garnet. Because garnet is apparent in even a cursory field examination, the appearance of the deposits lacking it compared with those containing it, accentuates the difference between them more than is actually warranted. The explanation of the lack of garnet at Cornwall is thought to lie in the great abundance of magnesia in comparison to lime in the metamorphosed rocks. Preponderance of magnesia over lime would tend to draw all the calcium into calcium-magnesium minerals (diopside and tremo-

lite-actinolite) instead of calcium-iron or calcium-aluminum minerals (andradite and grossularite). The tendency to form the calcium-magnesium silicates would be accentuated by the lack of iron and alumina in the limestone at the time that the silicate gangue minerals were formed, which took place before iron was introduced into the metamorphic aureole.

TABLE V.

MINERALOGICAL COMPARISON OF CONTACT-METAMORPHIC DEPOSITS.

Type of Deposit Number of Deposits	Iron 7 a, u	Copper 8 a, u	Other 5 a, u	Total 20 a, u	Cornwall X a, u
Garnet	5, –	7, –	3, 2	15, 2	–, X
Epidote	3, 2	5, –	3, –	11, 2	–, X
Vesuvianite	–, 1	2, 1	2, 2	4, 4	–, X
Diopside-hedenbergite	5, –	6, –	2, –	13, –	X, –
Actinolite-tremolite	4, 1	6, 1	1, 3	11, 5	X, –
Wollastonite	–, –	2, –	1, –	3, –	–, –
Calcite-dolomite	1, 3	7, 1	4, 1	12, 5	X, –
Quartz	1, 3	5, 3	3, –	9, 6	–, ?
Hornblende	–, –	1, –	4, –	5, –	–, X
Apatite	–, 2	–, 2	–, 2	–, 6	–, –
Scapolite	–, –	–, 1	1, 1	1, 2	–, X
Tourmaline	–, –	–, 1	1, 1	1, 2	–, X
Orthoclase	–, 1	–, 1	–, 2	–, 4	–, X
Plagioclase	–, 1	–, 2	–, 3	–, 6	–, X
Phlogopite-biotite	1, –	1, –	4, –	6, –	X, –
Chlorite	2, –	2, –	–, 3	4, 3	X, –
Pyrite	3, 3	8, –	3, 2	14, 5	X, –
Magnetite	7, –	6, 2	2, 1	15, 3	X, –
Chalcopyrite	–, 2	8, –	2, 3	9, 5	X, –
Hematite	3, 1	4, 1	1, –	8, 2	X, –
Sphalerite	–, 1	–, 4	–, 5	–, 10	–, X
Galena	–, –	–, 5	1, 2	1, 7	–, –

a = abundant, u = uncommon.

The paucity of epidote and vesuvianite at Cornwall may be accounted for by lack of introduced alumina, which is necessary for their formation. All the minerals containing alumina are confined to the beds that were shaly limestone before metamorphism, and thus the conclusion has been drawn that the exhalations did not carry alumina.

The mineralogical differences between Cornwall and the other deposits can be explained by two factors: lack of alumina in the

exhalations from the diabase, and the high magnesia content of the invaded rocks. No complete data were obtainable as to whether the exhalations forming the other deposits contained alumina, but it seems highly probable that they did.

Comparison with the French Creek Deposit.—A comparison of the French Creek and Cornwall deposits is included here because, of all those tabulated, it is the most similar to the Cornwall bodies.

The iron ore deposit at French Creek has been described by L. L. Smith,[48] who classifies it as belonging to the Cornwall type. However, there are several points of difference between this deposit and those at Cornwall. Both deposits are of contact-metamorphic origin and are genetically associated with diabase intrusives, but the French Creek deposit has been formed by replacement of pre-Cambrian marble and those at Cornwall, by replacement of magnesia-rich Cambrian limestone and dolomite.

The diabase intrusions at both mines are in general similar, but differ in their joint systems and mineralogy. The joint systems at French Creek are regular and the rock is not so shattered as at Cornwall. Microscopic study shows that the minerals of the two diabase bodies differ greatly. The feldspar at French Creek is reported to be acid plagioclase, whereas at Cornwall there are two kinds, labradorite and orthoclase. The pyroxenes are also different; normal augite occurs at French Creek, whereas enstatite and enstatite-augite or pigeonite are found at Cornwall. The opaque iron mineral in the diabase at Cornwall has been shown above to be largely ilmenite with a small amount of magnetite. Smith does not say whether he examined the opaque iron mineral in the diabase by reflected light or simply assumed it to be magnetite. Pegmatite dikes are found in the diabase at both mines but no aplite dikes are recorded from French Creek.

In the ore bodies themselves many similarities occur between the two deposits, but there are also differences. At French Creek,

[48] Smith, L. L.: The Magnetite Deposit at French Creek, Penna. Fourth Penna. Geol. Surv. Bull. M–14, 1931.

Smith lists the important gangue minerals in the order of decreasing abundance, as follows: calcite, chlorite, pyrite, actinolite, and talc, whereas at Cornwall they are: diopside, actinolite, phlogopite, chlorite, and calcite-dolomite. The explanation of this difference presents several difficulties. The great abundance of calcite at French Creek may be explained in part by the fact that the zone of magnetite replacement of the marble extends beyond the silicate zone. The presence of actinolite (and augite), as reported by Smith, instead of wollastonite in a contact-metamorphosed calcite marble seems rather unusual. The prominent place held by pyrite in the French Creek deposit is not duplicated at Cornwall, where pyrite is much less important than many of the other minerals. Smith notes the presence of tabular or "platy" magnetite at French Creek; this has been discussed at length above. The identification of more than one variety of magnetite is only possible with the use of great care as the color differences are extremely slight and it is possible that the different varieties have been overlooked in studying the French Creek deposit.

Smith considers the ore solutions at French Creek to have preceded the injection of the pegmatite dikes into the diabase. At Cornwall, the diabase pegmatite precedes the ore-forming solutions and is separated from them by the period of aplitic injection. Smith does not make it entirely clear whether the ore-forming solutions originated through differentiation of the coarse-grained part of the adjacent diabase dike or through differentiation of the underlying parent magma of the diabase.

SUMMARY OF CONCLUSIONS.

Rocks.—The stratigraphy of the region had been worked out thoroughly by Stose and Jonas previous to the beginning of the study by the writer, who added little to this subject except tracing the boundaries of the rock formations, and the study of the Triassic igneous rocks. The so-called diabase is in reality a coarse-grained igneous rock having approximately the composition of a quartz gabbro. In general the rock shows signs of

slight alteration such as might be caused by an abundant, water-rich, late-crystallizing rest-magma. In addition, differentiation has taken place in the diabase, producing pegmatite and aplite dikes and rest-magma segregations, as well as micro-veins within the early crystallized border of the dike.

In the study of the mineralogy of the diabase several interesting features were noted. Orthoclase was found to be a common constituent of the diabase, ranging up to 20 per cent. of the rock. The pyroxenes were found to be enstatite and pigeonite (enstatite-augite) rather than common augite. Ilmenite is more abundant in the diabase than magnetite.

Extensive contact metamorphism surrounds the large Triassic intrusives. Three types of aureoles are represented, corresponding to the three varieties of rock intruded by the diabase. The first and most abundant was produced by the action of the diabase on the Triassic shales, sandstones, and conglomerates. Contact metamorphism has removed the red color from all of them, the bleaching commonly extending up to half a mile from the contact. In addition, narrow zones of more intense metamorphism occur along the contacts where small areas of hornfels and segregations of specular hematite are found.

The second type of aureole occurs where the diabase has intruded the shale at the top of the Conococheague formation, producing a cordierite-andalusite hornfels. This type of aureole was produced by the heat of the intrusion alone; no evidence of addition of material was found.

The third type of aureole has been produced by the action of the diabase intrusion on the Conococheague limestone at Cornwall, and on other limestones in other parts of Pennsylvania. The iron ore deposits occur in this type of aureole, and it will be considered more fully in the discussion of the ore deposits.

Ore Deposits.—The contact metamorphism, which gave rise to the ore deposits at Cornwall, proceeded in two stages separated from each other by a time interval. During the first stage, which took place at the time the diabase was intruded, the rocks

were altered chiefly by means of heat, causing recrystallization of minerals already present. It was accompanied by slight additions of material which silicified small portions of limestone directly on the diabase-limestone contact. During the second stage, which occurred later, when the diabase was considerably cooler, introduced material intensively replaced the carbonates of the limestone. The ore was formed during this second process.

The source of the ore-forming solutions is considered to be in the adjacent diabase, where the slowly cooling interior of the intrusion formed a rest-magma, rich in potash, iron, and water. Being under great pressure (due to the crystallization of a large part of the rock), the less viscous part of the rest-magma escaped into the surrounding rocks along joints and fissures in the solidified border of the diabase. The escaping part of the rest-magma was composed of a water-rich solution carrying potash, iron, silica, copper, sulphur, "mineralizers," and minute amounts of a few additional elements. It is believed that the solutions were in a liquid state even though they were above the critical temperature of pure water, since it has been shown that the addition of small amounts of certain substances such as potash will materially raise the critical temperature of water.

The minerals in the ore deposit are characteristic of high-temperature deposits. Simple oxides and high-temperature silicates are the common minerals. Three varieties of magnetite were found in the Cornwall deposits; one is an anisotropic variation, whereas the other two are normal magnetite and the oxidized form, maghemite, both of which have been discussed previously by several investigators. The minerals in the deposit are zonally arranged in respect to the diabase dike. The greater abundance of magnetite along the hanging walls of the ore bodies than along the footwalls is ascribed, not to a zonal arrangement in relation to the diabase, but to the presence along the hanging walls of a zone of actinolite which was more readily replaced by magnetite than the diopside that forms a zone along the footwalls. Chalcopyrite, on the other hand, is distributed in zones, being more

abundant along the hanging walls and in the upper parts of the ore bodies than along the footwalls and in the lower parts.

Comparison with Other Deposits.—A mineralogical comparison is made between the Cornwall deposits and twenty other contact-metamorphic deposits. The results show that the Cornwall deposits are quite similar to the others in most respects. A lack of abundant garnet and epidote at Cornwall is noted and is explained by two factors: The paucity of alumina in the exhalations from the diabase, and the high magnesia content of the limestones and dolomites that have been replaced to form the ore.

The Cornwall deposits are contrasted with the French Creek deposit and both are found to belong to the Cornwall type. However, many differences were found between them on close examination. The diabase at Cornwall contains labradorite, orthoclase, enstatite, pigeonite, and ilmenite, whereas that at French Creek contains acid plagioclase, augite and magnetite. The relative abundance of the gangue minerals at the two deposits is different. Calcite is the most abundant gangue mineral at French Creek, whereas at Cornwall the silicates, diopside and actinolite, greatly predominate over the carbonates.

From detailed comparisons of the Cornwall deposits with other contact-metamorphic deposits (omitted from this paper), some tentative conclusions were reached as to the relationship between igneous rock types and the character of the metamorphic aureoles along their contacts with limestone. The following tentative classification is suggested here but many more deposits must be examined and correlated before its usefulness is proved.

1. Quartz monzonite and granodiorite are associated with chalcopyrite deposits carrying small amounts of magnetite and abundant high-temperature silicate gangue. Examples are San Francisco, Utah, Yerington, Nevada, and Mackay district, Idaho.

2. Quartz diorite and diorite are associated with magnetite deposits carrying small amounts of chalcopyrite and abundant high-temperature silicate gangue. Examples are Iron Springs, Utah, Taylor Peak, Colorado, and Hanover, New Mexico.

3. Quartz gabbro and diabase are associated with magnetite deposits carrying small amounts of chalcopyrite and moderate to abundant non-aluminous silicate gangue. The Cornwall type of deposits fall into this group. Examples are Cornwall, Pennsylvania, and French Creek, Pennsylvania.

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FINE GOLD AND PLATINUM OF SNAKE RIVER, IDAHO.

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INTRODUCTION.

KEEN interest in deposits of fine gold along the Snake River, Idaho, has been revived and a few favored localities of concentration along its course of over 700 miles in and bordering the state are being worked at the present time. The presence of platinum and associated metals is confirmed, and the true nugget-like character of both gold and platinum grains attracts attention. The gold from the deposits examined is truly "flour" gold, since it takes approximately 5000 grains or "colors" to weigh 1 cent in value. Improved methods of recovery may justify present optimism in these widespread deposits. A general bibliography, covering many related features of the deposits in more or less detail, is appended.

GENERAL FEATURES.

Acknowledgments and Field Work.—The writer especially wishes to express his gratitude to Professor A. W. Fahrenwald and Mr. Joseph Newton, of the School of Mines, University of Idaho, for their coöperation in making numerous tests of samples of gravel. Appreciation is expressed for the facilities and use of equipment of the School of Mines, University of Idaho, Moscow, Idaho. The writer also is greatly indebted to Mr. John W. Eagleson, President of the Tyceska Gold Mining Company, for his coöperation in supplying material, and to Mr. J. V. Shanklin, operator on the Wilson Ranch placer, for samples furnished.

Samples studied in detail were collected during the spring and early summer of 1932 on the property of the Tyceska Gold Mining Company in Elmore county at locations several miles east of King Hill, and in Owyhee county on the south side of the river

between King Hill and Glenns Ferry, Idaho. At this time samples were also collected from the diggings on the Frank E. Wilson ranch, one mile south of Hammett, Idaho.

Location of the Deposits.—Deposits of fine gold occur along the Snake River as it meanders across the entire southern part of the state. Similar deposits continue along the river as it forms the boundary between Idaho and the states of Oregon and Washington. Operations have been largely confined to deposits along the river above the Grand Canyon of the Snake. In fact, gold is present over practically its entire length, for deposits are found near the headwaters [1] on Upper Snake River and Pacific Creek in the Yellowstone Park region, and they persist throughout the course of the river.

History of Operations.—Placer operations are reported on the Upper Snake River in the early 60's. The gravels have been worked by special "machines" and by nearly every commonly known method, including hand operations and great dredges handling up to 2500 cu. yds. daily. The conclusions of Maguire,[2] that the large operations are not a success, have been born out up to the present time. He states that skim bar miners averaged from $1.00 to $4.00 a day with rockers and these figures are probably representative of most of the small to moderate-scale operations. A very few properties, chiefly where coarse gold was present, may have paid from $19.00 to $100.00 a day per man, as recorded by Bancroft.[3] Deposits along the Snake River may prove to be a better "meal ticket" than many of the old worked-over placer deposits.

Some half dozen dredges have been installed along the river and according to R. N. Bell, records show that one $10,000 dividend paid by the first Sweetzer-Burrows Dredging Company's operation was the only dividend ever paid by the dredge companies. He estimated in 1906 [4] that $1,000,000 worth of plants

[1] Iddings, J. P., Weed, W. H., and Hague, Arnold: Geology of the Yellowstone National Park. U. S. Geol. Survey, Mon. 32, pt. 2, pp. 184–189 and atlas, 1899.

[2] Maguire, Don: Snake River Gold Fields. Mines and Minerals, vol. 20, pp. 56–58, 1899.

[3] Bancroft, H. H.: History of Washington, Idaho, and Montana. Works, vol. 31, 1890.

[4] Bell, R. N.: Annual report, Idaho Inspector of Mines, 1906.

had been installed along the Snake. But one does not wonder at the repeated and varied attempts at recovery when Maguire [5] estimated the gravels contained $2,000,000,000 in gold. Recent tests by Fahrenwald [6] on the flour gold show highly satisfactory recovery by flotation. Platinum, which has been identified in the concentrates, is amenable to flotation. The percentage of recovery has not been determined, since platinum is present only in very minor amounts.

Source of the Gold.—The source of so much fine gold and associated platinum still remains a question for conjecture. Washburn,[7] in summing up the suggestions of different writers to the effect that the gold has been supplied by tributary streams and by adjacent lavas, concluded it was probably derived from both sources. Few, if any, now accept the theory advanced by Capt. N. L. Turner (see Bell [8]), that the gold was precipitated from solution in a great inland lake.

THE GOLD DEPOSITS.

Types of Deposit.—The deposits fall under the general classification of bench placers and river bar placers; the small but important skim bar gravels being but a particular type of river bar placers. Opinion is reasonably well agreed upon the general distribution of values in the gravel and the character of the deposits. Best values seem to come in fine gravel up to ¾ in. in diameter. At a deposit several miles east of King Hill exceptionally good values are found in fine gravel associated with large boulders up to 5 ft. in diameter. Numerous conditions of deposition have been recorded in different investigations. Washburn [9] describes and illustrates deposition and enrichment in relation to bends in the river, also deposits occurring opposite or alongside of the bank

[5] *Op. cit.*

[6] Fahrenwald, A. W., Professor of Metallurgy and Ore Dressing, School of Mines, Univ. of Idaho, Moscow, Idaho.

[7] Washburn, W. H.: Gold in Snake River Gravel Bars. Min. and Sci. Press, vol. 81, p. 610, 1900.

[8] Bell, R. N.: The Origin of the Fine Gold of the Snake. Eng. and Min. Jour., vol. 73, pp. 143–144, 1902.

[9] *Idem.*

of the river from a previous deposit. Skim bars are discussed and illustrated in detail by Hill [10] and he states that lenses in the terrace or bench gravel correspond to skim bar gravel of the present day, which yields more than coarse gravel. Several of these pay streaks from a few to 10 feet apart, separated by lean gravel, have formed some of the more attractive deposits. Instances have been noted where the richest pay streak is confined to a few inches of gravel at the surface of bars.[11] Narrow pay streaks [12] are reported to run as high as $2.50 per yard and this amount is exceeded in a few instances. Overburden, generally sandy loam, may carry from a few cents to 20 cents a yard. Bell [13] believes that few gravel bars along the Snake River carry an average value of 30 cents per cu. yd. for a depth of 10 ft., but that there are probably millions of yards of sand and gravel adapted to dredge, having 5 cents to 15 cents per yd. of savable gold.

Lenses cemented by calcium carbonate are common in the deposits and may carry high values. When the gravel is reworked by the ever-changing river channel, coated gold is liberated and redeposited. Much less clay and silica are deposited on the flakes. Only a very small proportion of the gold is so completely covered that it is not recovered by flotation. Black sand is abundant and, contrary to popular belief, in itself probably carries no gold. Extremely thin flakes and minute grains persistently cling to the minerals separated by the magnet.

An interesting comparison brought out in the report of Day and Richards [14] reveals that ilmenite is an important constituent of the sands from Snake River and that it is sparingly present in the black sands of the Pacific slope, where chromite is abundant.

It is the writer's experience that estimates of yardage values need revision. Conclusions have been based on insufficient sampl-

[10] Hill, J. M.: Notes on the Fine Gold of the Snake River, Idaho. U. S. Geol. Survey Bull. 620, pp. 271–294, 1916.

[11] Powell, F.: Gold Dredging on Snake River in Idaho. Eng. and Min. Jour., vol. 70, pp. 395–396, 1900.

[12] Washburn, W. H., *Op. cit.*

[13] Bell, R. N.: Annual report, Idaho Inspector of Mines, 1904.

[14] Day, D. T., and Richards, R. H.: Useful Minerals in the Black Sands of the Pacific Slope. U. S. Geol. Survey, Mineral Resources, 1905, pp. 1175–1258, 1906.

ing or on savable values, the proportion of which to the total gold content has been partly conjecture. Recoverable values probably vary from about 50 per cent in the case of some of the smaller operations to upwards of 90 per cent. reported for a few of the large dredge operations. In checking a deposit, the operator suggested he was saving 90 per cent. of the gold, but sampling and a careful check showed he was recovering less than 70 per cent. Samples panned down fairly closely will save about 75 to 80 per cent. of the gold, for some of it washes over with the abundant heavy sand. It may be expected that a few of the small bars which have been estimated to carry average values of 30 cents a yard for depths up to 10 feet may run as high as 45 cents a yard.

Character of the Gold.—The fine gold of the Snake River, although quite uniform in character, varies to some extent. Adjacent deposits have locally supplied coarse gold, and large tributary streams affect both size and fineness. Washburn [15] notes that the flakes at the head of a deposit are coarser and more abundant, becoming finer and fewer and spreading out below. Samples of gold collected from river bar and bench placers along the river from Hammett to several miles east of King Hill are surprisingly similar. The King Hill concentrates may contain a slightly greater proportion of large flakes. A miscellaneous group of the flour gold is shown in Fig. 2. Individual particles are seldom noted larger than 0.5 mm. in diameter, although in instances they attain 1 mm. Minute grains are found in flotation concentrates that are even smaller than those shown in Fig. 2. Representative samples of the fine gold from the above localities, when weighed, counted, and calculated, show that it takes approximately 5000 colors to be worth 1 cent, or nearly 10,000,000 particles to an ounce. An estimate of the smallest particles shown in Fig. 2 indicates that it takes from 40,000 to 60,000 of these flakes to be worth one cent. Much of the Snake River "flour" gold may be expected to average from 3000 to 5000 particles to one cent. Previous estimates of the number of colors to one cent in value rarely exceeded 1000 to 2000 particles. Most

[15] *Op. cit.*

particles are thin flakes, although small rounded grains are present and parts of certain grains may be much thicker than the balance. Thickness (of a number) of flakes ranges from 0.005 mm. to 0.02 mm. Flour gold floats readily if exposed to air for an instant.

The color of the gold is deep yellow and it appears bright to the naked eye. Under the microscope the rough, pitted surface has the true character of flattened or thin disk-shaped gold nuggets (Fig. 1). Probably the cavities are largely due to the removal by solution of impurities including silver, which the high grade of the gold would indicate. Humic acids attack the gold and may aid in a small way in producing the rugged condition. Occasional particles have a distinct brownish cast. Freise,[16] in examining Brazilian placers, shows that the brown coating carries from 2.85 to 3.5 per cent. Fe_2O_3 and can be considered as $C_2O_7H_2Fe$, humate of iron. The brown cast in some instances is considered by Hill [17] to be iron hydroxide; the possibility of manganese oxide must also be considered.

The shapes of the gold particles are indeed varied. Figs. 1, 2, and 3 give a partial idea of the many beautiful nugget-like forms revealed by the microscope. The effects of abrasion are very evident. Edges may be rolled, turned over, and flattened, or bent to such an extent as to form the cup-shaped particles often noted by writers. Fig. 2(*a*) shows a particle having a jagged tear in the upper edge.

There has been much speculation concerning the nature of the gray to white coating on the individual gold grains. Fig. 2(*b*) shows coatings on particles that may cover one or both sides, leaving exposed merely the bright edge, as shown in the grain adjacent to the largest flake. This coating is calcium carbonate, as in the case of most of the coated particles in the deposits examined. Material coating the particle of platinum, Fig. 3(*a*), is not calcium carbonate but is probably clay, colloidal silica, or cryptocrystalline quartz. Similar material is found on gold

[16] Freise, F. W.: The Transportation of Gold by Organic Underground Solutions. Econ. Geol., vol. 26, No. 4, pp. 421–422, 1931.

[17] *Op. cit.*, p. 280.

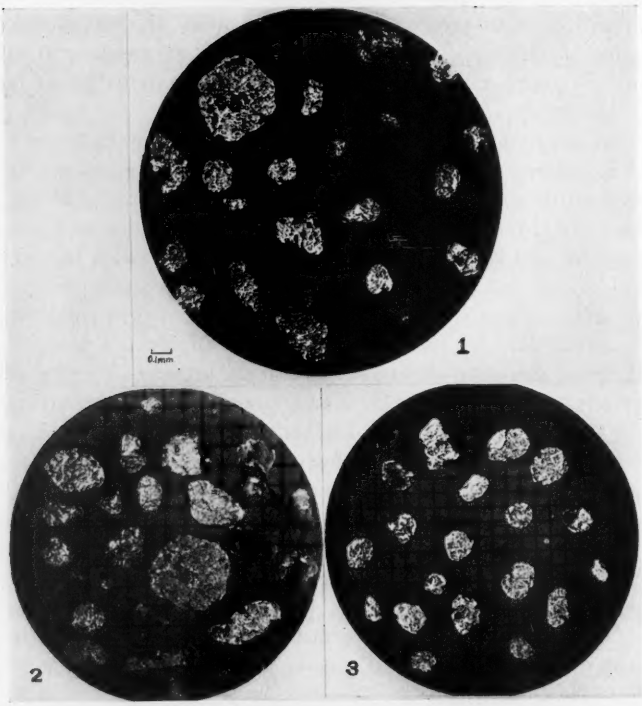

FIG. 1. Photomicrograph showing detail and depth of cavities on the rugged surfaces of the fine "flour" gold.

FIG. 2. Photomicrograph of fine gold from Snake River, Idaho. Miscellaneous group indicating size range and showing nugget-like appearance. Shows flake (*a*) with torn edge and particles; (*b*) in part or almost wholly covered with calcium carbonate ($CaCO_3$). The side of individual squares represents 0.1 mm.

FIG. 3. Photomicrograph of platinum and associated metals from Snake River placers. Note less variation in size than gold. Grain (*a*) with gray coating composed of clay or silica; edge (*b*) turned over and flattened; cup shape (*c*) partly developed. The side of individual squares represents 0.075 mm.

particles but in much smaller proportion than calcium carbonate.

Gold from the King Hill section is reported to be worth $19.72 an ounce, representing a fineness of 954. Shannon [18] reports gold from Bingham and Bonneville counties worth $19.60 an ounce, or 951 fineness. This is an evidence of purification during the process of transportation. Washburn [19] mentions that above the mouth of the Boise River the Snake River gold is worth $17.00 to $19.00 per ounce, whereas below, it runs from $14.00 to $16.00 an ounce. Above the Boise River, 1200 colors are worth only one cent, but below the junction of the Boise and Snake Rivers it takes only 900 colors to make one cent. The number of colors to the cent is probably estimated from ordinarily recoverable gold, yet their relative relationship shows the effect of large tributary streams on the nature of the gold.

PLATINUM AND ASSOCIATED METALS.

The minute particles of platinum and associated metals have been appropriately described by Bell [20] as "gray-white metal in impalpably fine particles." Day [21] definitely reported platinum in black sands collected along the Snake River. Qualitative chemical tests of the grains react principally for platinum but indicate the presence of other minerals of the platinum group. Many of the grains are slightly magnetic, indicating the presence of iron. Fig. 3 shows flattened grains of platinum which tend to be smoother as well as thicker than gold particles. Only about 150 grains were separated, so it is not deemed advisable to draw definite conclusions as to size, although the group shown seems to be representative. Oval and rounded shapes predominate. The platinum grains do not reach either the maximum or minimum sizes observed in gold particles. The mean or average size appears to be only several hundredths of a millimeter smaller

[18] Shannon, E. V.: The Minerals of Idaho. U. S. National Museum Bull. 131, pp. 50–70, 75–76, 1926.

[19] *Op. cit.*

[20] *Op. cit.*, p. 144.

[21] Day, D. T., and Richards, R. H.: Investigations of Black Sands from Placer Mines. U. S. Geol. Survey Bull. 285, pp. 150–163, 1906.

than that of the flour gold. The material also shows the effects of transportation and abrasion. Fig. 3(*b*) shows a particle that has had an edge turned over and flattened, and Fig. 3(*c*) shows partial development of a cup-shaped flake.

The present investigation indicates an approximate proportion of about one platinum grain to two or three thousand gold particles. The platinum is recovered by flotation but would have little economic importance.

Moscow, Idaho.

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THE ILMENITE–APATITE DEPOSITS OF WEST-CENTRAL VIRGINIA.

C. W. RYAN.

INTRODUCTION.

THE existence of large titanium deposits in Amherst and Nelson Counties, Virginia, has been known for a number of years, and the geological occurrences together with the economic possibilities of the deposits have been discussed at length. As early as 1878 the outcroppings of hard ilmenite ore on the Warwick farm, situated on the northern boundary of Amherst County, attracted attention, and the mineral rights on this property were bought by the Philadelphia Reading Coal and Iron Company,[1] who planned to utilize the ore in the manufacture of iron. This, however, was given up, probably due to the refractory nature of the ore occasioned by its high titanium content. At intervals other activities followed without apparent success, for example, the purchase by the Virginia Phosphate and Paint Company in 1894 of the Giles tract northwest of Roseland, Nelson County, and in the following year the Quinn place. This company tried unsuccessfully to utilize the ore in the manufacture of paint and fertilizer. In 1900 the American Rutile Company opened a deposit of rutile-ilmenite ore at Roseland,[1] and since that year with various periods of inactivity it has continued successfully in the production of rutile and ilmenite concentrates. It is today the largest producer of rutile for the domestic market.

It is noteworthy that with the exception of the American Rutile Company, whose deposit is a rutile-ilmenite ore disseminated through syenite, all other activities were centered around the hard dike-like bodies of ilmenite-apatite nelsonite. Recent investigations have disclosed the existence of large deposits consisting

[1] Watson, Thos. L., and Taber, Stephen: Geology of the Titanium and Apatite Deposits. Va. Geol. Survey Bull. No. 111–A, pp. 48–49.

principally of ilmenite, apatite, and mafic minerals, which for purposes of distinction and by virtue of the ratios of different minerals present may be termed disseminated ores. These deposits will be discussed here with regard to the more important geological features, characteristics of the ore affecting mechanical recovery, and their possible economic importance.

GENERAL GEOLOGY.

According to Watson [2] the co-magmatic rocks of the district, consisting of quartz-biotite-monzonite-gneiss and schists, syenite, gabbro and diabase, are thought to be of pre-Cambrian age. A single mass of syenite extends some sixteen miles in a northeasterly direction and has a width of about two and one-half miles. Numerous dikes or apophyses extend from the ends of this mass into the monzonite-gneiss by which it is entirely surrounded. The monzonite-gneiss covers large areas in the Piedmont section of Virginia along the base of the Blue Ridge Mountains both within and beyond the limits of the area under discussion. Gabbro occurs principally within and near the borders of the syenite; various gradations of the two rocks have been noted. Diabase, apparently the youngest of the rocks, cuts the syenite and monzonite in narrow dikes. Various stages of regional metamorphism are visible in all the country rocks.[3]

Monzonite gneiss and syenite are intruded by numerous narrow dikes of nelsonite, many of which are composed mainly of apatite and titanium minerals. The chief mineral constituents of some of the types are, ilmenite with apatite, ilmenite with rutile and apatite, rutile with apatite, titaniferous magnetite with biotite and minor quantities of apatite, and hornblende nelsonite composed of ilmenite with apatite and hornblende or its alteration product chlorite. The most prominent of these dikes are located in the border phases of both monzonite and syenite in dikes not exceeding, 1500 feet in length, with a tendency to pinch and swell after the manner of typical lenticular ore bodies. The strike of in-

[2] Watson and Taber, *op. cit.*, p. 56.

[3] For description of the microscopic features of the ores, see Watson, *op. cit.*

dividual dikes ranges from about N. 45° W. to N. 45° E., with a general tendency of the majority to follow the northeast-southwest schistosity of the inclosing rocks. In texture, they are even-granular with the rounded crystals of apatite partly or entirely enveloped by irregular grains of ilmenite. In a few instances ilmenite has been found in crystallized form.

THE DISSEMINATED ORES.

The disseminated ores resemble some of the above-mentioned dike ores. There is a marked similarity to biotite nelsonite and hornblende nelsonite, and it is possible that they may be correlated as gradations of these two types of dike ore. This likelihood is strengthened by textural and mineralogical similarity of the ores.

In both dike and disseminated ores an even granular texture predominates. The relation between ilmenite and apatite grains is approximately the same, clusters of ilmenite grains enveloping the rounded crystals of apatite. More free grains of both minerals appear, however, because of the decreased concentration of

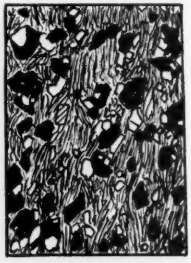


FIG. 1. Diagram of disseminated ores.

ore minerals. The mafic minerals appear in plated forms. Fig. 1 illustrates in diagram the arrangement of minerals in the disseminated ores. Black grains are ilmenite, white are apatite, and fibrous and cross-hatched areas are mafic minerals.

The disseminated ores are located in the border phases of the syenite and in the inclosing monzonite. It is not thought that

close association with the syenite was necessary for the formation of these ores, however, since large deposits have been found at some distance from it, entirely surrounded by monzonite. The proximity of the syenite has in all probability influenced the composition of the constituent minerals though not the tendency to segregate them into ore bodies.

The size of the ore bodies is variable, ranging from small lenses to bodies of great dimensions. The width in certain cases approaches 400 feet and the length one half mile. The general trend of the ore bodies is northeast and southwest parallel to the schistosity of the country rock. The dip is normally southeast on a steep angle. Faulting may cause a reversal of dip.

The relationship of the ore bodies to the inclosing rocks is normal. There is a tendency gradually to blend or grade into the latter at the borders especially on the hanging-wall side. In shape they are roughly lenticular with apophyses extending from the ends into the country rock. The crustal movements that metamorphosed the latter, appear to have exerted similar influences upon the ore bodies. All faults are later than the period of ore formation.

The surface evidences of disseminated ore bodies are meager. In the process of weathering the breaking down of gangue minerals and apatite leaves merely a heavy clay impregnated with ilmenite. Occasional outcrops may be observed but these are generally insignificant and much altered.

TEXTURE AND STRUCTURE OF DISSEMINATED ORE BODIES.

Within the ore bodies there is a gradual diminution of gneissic texture at increasing distances from the country rock. The border facies exhibit this texture in well-preserved outlines with a small sprinkling of ilmenite and apatite grains intermixed. Toward the center of the mass this is finally obliterated and is replaced by the even-granular texture characteristic of the nelsonites. Here the ore is massive and blocky, only the widely spaced slip-planes of minor faults breaking the uniformity. Close examination, however, discloses that although the granular nature

of the ore minerals has been preserved, the mafic minerals have been drawn out into plates that bend around the clusters of ore minerals in a manner faintly suggestive of the "augen" facies of the monzonite.

In weathering, the gangue minerals of the disseminated ores are altered to more complex forms. They take on in general a brownish color, and considerable limonite is in evidence. The ore minerals, as may be expected, react in a different way. Apatite is taken into solution and leaves merely skeletonized forms. Ilmenite is altered more slowly, and leucoxene is developed superficially and along cleavage cracks. Where an excess of ferric iron is present, red hematite is formed. The alteration of the mineral aggregate promotes the development of a soft, easily crumbled mass. This grades with depth to a rather tough aggregate in the unweathered zone. The normal color of the unaltered ore is green.

Of the ore minerals ilmenite is present in greater concentration than apatite, a fact which is characteristic of most types of nelsonite ores. In a few isolated cases, however, the apatite constituent is richest, but this is exceptional. The concentration of ore minerals in the deposits is variable, even within a single ore body.

Injected into the disseminated ores and paralleling the general schistosity are narrow dikes of the hard or concentrated variety of nelsonite. Some of these dikes are of the hard variety in which the ilmenite is poorly crystallized. Much float is derived from this type because of its high resistance to weathering. Another variety found is of sugary texture with a higher ratio of apatite. This crumbles easily and leaves no float. Alternating with these hard dikes are horses or lenses of basic rock of felsitic texture, possibly the amphibolite mentioned in Watson's account of the deposits.[4]

COMPOSITION OF THE ORE.

In Table I is given a complete analysis of the disseminated ore, with calculated norm, taken from Watson's treatise.[5] Al-

[4] Watson and Taber, *op. cit.*, p. 199.

[5] *Idem*, p. 134.

though the composition of the ores varies considerably from this example, it represents the approximate proportions of the ore minerals.

TABLE I.

Analysis of Hornblende Nelsonite. Wm. M. Thornton, Jr., Analyst.		Calculated Norm.	
SiO_2	20.02	Quartz	7.50
Al_2O_3	2.64	Orthoclase	2.22
Fe_2O_3	11.75	Albite	1.57
FeO	16.98	Corundum	1.84
MgO	5.93	Hypersthene	14.80
CaO	10.27	Hematite	11.68
Na_2O	.23	Ilmenite	36.33
K_2O	.39	Titanite	3.53
H_2O —	.71	Rutile	.16
H_2O +	2.47	Apatite	16.80
TiO_2	20.73	Water	3.18
P_2O_5	7.34		
MnO_2	.23		
Cl	.02		
F	.31		
CO_2	Trace		
Total	100.02	Total	99.61

The quartz is of a distinctive type peculiar to the ores and to the inclosing rocks of the district. It is blue in color, due to the inclusion of fine needles of rutile.[6] As found in the ore deposits it is generally in small, irregular grains. In the syenite it occurs as irregular lenses several inches in length. Smaller lenses are more characteristic of the monzonite.

The ilmenite of the district carries some hematite in the form of inclusions or intimate crystallographic intergrowths. In the presence of an excess of titanium the hematite radical is thought to be in combination with the former in the form of a ferric titanate.[7] Small percentages of chromium and vanadium appear in analyses of the pure ilmenite.

The apatite of the district carries fluorine as well as small percentages of chlorine.

[6] *Idem*, p. 215.

[7] *Idem*, p. 226.

MINING AND MILLING THE TITANIUM ORES.

All mining in the district is done by open-cut methods.

In the production of concentrates, the final step is the use of magnetic separators upon processed sands. Of the two companies operating at present in the district, the American Rutile Company produces rutile concentrates and ilmenite concentrates. The Southern Mineral Products Corporation produces ilmenite concentrates and apatite concentrates.[8] These two concentrates are treated in separate chemical units for the production of titanium dioxide and phosphoric acid.[9]

PROPERTIES OF THE ORE INFLUENCING MILL RECOVERY.

Treating the subject in a cursory manner, the principal characteristics of disseminated nelsonite ore that influence methods applicable in ore-dressing are: (1) the ease with which the ore is ground, (2) relatively even distribution of ore particles in the middle sizes, (3) the difference in toughness of the mineral constituents, (4) textural relationship of the ore minerals, (5) the wide difference in magnetic attractability of the minerals. Of these considerations the first two are subject to considerable change in zones of intense weathering.

In processing greatly weathered ore and to a less extent with partly weathered ore, primary crushing and fine grinding produce a high percentage of slimes. This is least noticeable in ilmenite due to its greater hardness and toughness, is quite apparent in apatite, and is especially true of the micaceous mafic minerals. From these a large amount of muddy slimes are produced.

In the unweathered or slightly weathered zones the grain size of ore minerals is fairly uniform, ranging from 0.2 mm. to 2.0 mm. in ilmenite and from 0.2 mm. to 1.2 mm. in apatite. Gangue minerals occur in platy aggregates several millimeters in length.

Ilmenite resists grinding action, furnishing a small ratio of slimes and a high percentage of oversize which acts as a natural abrasive. Contact of this material with apatite and gangue results in rapid sliming of both.

[8] U. S. Geol. Survey, Mineral Resources, 1930, Part 1, p. 287.

[9] Manufacturer's Record, Apr. 9, 1931, pp. 38–40.

Because of its natural position within clusters of ilmenite grains much of the apatite is subjected to considerable abrasion before it is freed by grinding. Prolonged contact with the sharp edges of ilmenite grains accentuates this condition, and as a result much slime is produced.

Separation of the various minerals present in processed sand is effected by taking advantage of their different magnetic properties. In their order of decreasing magnetic attractability they are, ilmenite, gangue minerals, and apatite. A clean separation of the valuable mineral and gangue is affected in some degree by incomplete unlocking of grains and by thermic alteration of their magnetic properties.

ECONOMIC POSSIBILITIES.

No accurate estimate of the available tonnage of ore in the district can be made at present. The total area underlain by the several known deposits of disseminated ore is very considerable, but their depth cannot be estimated, although it seems probable that it may be several hundred feet. Neglecting the numerous dike-like bodies of hard nelsonite ore, the disseminated ores represent a large tonnage.

Taking into consideration the wide distribution of titanium through the district, and the exceptional richness in titanium of the plutonic rocks encountered, it seems improbable that the number and variety of commercial ore bodies is limited to those already discovered.

Physical conditions related to the deposits are favorable to economic recovery of the valuable minerals. Distances to water, timber, adequate electric power, highway and railway transportation are short, not exceeding ten miles in any case. The disseminated ores may be worked cheaply by open-cut methods. The dike ores require shaft or tunnel mining, with considerable timbering and pumping. The climate is favorable for year-round production.

The Central-Virginia field is practically untouched so far as concerns tonnages already removed. The future of mining in

the district depends upon the success with which its ilmenite is adapted to the manufacture of white pigment (displacing foreign ore), and the degree to which its apatite will replace, in the phosphoric acid and fertilizer trade, ore from other diminishing sources of supply. The apatite is highly suited to the manufacture of phosphoric acid. It is not thought that mechanical recovery of the valuable minerals in a usable form presents any serious obstacles.

DOMESTIC CONSUMPTION OF ILMENITE.

The domestic consumption of ilmenite in excess of the small tonnage produced in this country in 1929 was 25,072 short tons. Most of this ore came from Travancore in India and from Senegal.[10] Domestic consumption of ilmenite has been on the increase for some years and it is possible that with the return of normal times this will in a measure continue. Whether foreign producers can continue to supply a growing demand and whether domestic producers will be able to compete in the price of their product with those now supplying the market can not be predicted. Should the entire domestic market be thrown open to domestic producers it is believed that the tonnage available in the Virginia field will supply that market for a great many years.

PRINCIPAL USES OF TITANIUM.

The principal use of titanium at present is in the oxide form, which makes an excellent white pigment. It has a superior whiteness and greater hiding power than most white pigments and does not react with solvents ordinarily used. Besides being used in combination with inert fillers such as barium sulphate and calcium sulphate and lithopone, it is marketed as pure titanium dioxide. In pure form it is particularly desirable for lacquers, since very small proportions of the pigment are required and improvement in gloss, ease of application, increase of elasticity and continuous

[10] U. S. Geol. Survey, Mineral Resources, 1930, Part 1, p. 290.

film result. Titanium in the form of a ferro-alloy is employed in the purification of steel. It is likewise used as strippers and mordents in the dye industry, as a refractory coloring matter in ceramics, and as an incandescent medium in electricity. An increasing number of uses for titanium may be expected in the future.

LYNCHBURG, VIRGINIA.

ORIGIN OF THE FROOD ORE DEPOSIT.

B. C. FREEMAN.

THE phenomenally rich ore body of the Frood mine is situated about two and a half miles north of Sudbury, Ontario, and about a mile southeast of the Southern Nickel Range. It is the property of the International Nickel Company, who refer to it as the No. 3 mine, but it is generally called the Frood mine, after one of the original stakers.

The outcrop of the ore body is a gossan-covered ridge rising about sixty feet above the surrounding swampy ground. The ore body is near the southwest end of a strip of gossan-covered ridges and knolls that extend for about two miles and attain a maximum width of nearly a thousand feet. It has the form of a sill in the Sudbury series.

The Sudbury series (strike about N. 35° E., dip about 65° NE.) is the oldest formation in the Frood area. Its character and distribution indicate deposition as continental sediments southeast of a mountain range. The sediments contain interbedded basic lava flows and intrusive basic rocks, the greenstones of this report. After a prolonged period of erosion, the volcanic and sedimentary rocks of the Whitewater series were laid down; they outcrop more than five miles away to the northwest. Later the norite-micropegmatite of the Nickel Eruptive was intruded along the plane of the Sudbury-Whitewater unconformity. Its outcrop lies roughly parallel to the gossan-covered ridges and about a mile to the northwest. About the same time, although a little later, the granite was intruded which now outcrops between the norite and the Sudbury series.

There has been disagreement over the character of the rock in which the Frood ore occurs. Barlow [1] and Coleman [2] believe

[1] Barlow, A. E.: Geol. Survey, Can., Ann. Rept., vol. 14, Pt. H, p. 120, 1901.

[2] Coleman, A. P.: Rept. Ont. Bur. Mines, vol. 12, pp. 277 and 279, 1903.

it to be norite. Howe [3] found no trace of the unaltered original rock but believes that it must have been related to the norite. Dickson [4] also regards the host rock as much altered norite, as do Tolman and Rogers [5] as well. Walker [6] said that the nickel-bearing rock at the Stobie mine indicates an approach to amphibolite, and Knight [7] believes the host rock to be a diorite, unrelated to the norite of the Nickel Eruptive.

The graywacke of the Sudbury series is a somewhat massive, fine-grained, granular gray schist. The principal constituents are quartz and biotite. Plagioclase feldspar and hornblende are present in varying, usually small, amounts, and secondary chlorite and zircon are commonly present. The chemical composition is similar to that of a sandy shale. In the vicinity of the gossan knolls it contains irregular blebs of sulphides that look exactly like those in the well known "pyrrhotite-norite." In some places vertical shear zones separate gossan and graywacke, but in others there is a complete transition between the two. This is well shown at *A* and *C* on Fig. 1. At various places, particularly at *C* on the map, the graywacke presents conglomeratic phases in which cobbles of quartzite, of massive greenstone, and of greenstone lava showing flow lines, are lying in a graywacke matrix. In addition to the lava cobbles, lava flows interbedded with graywacke occur and are well shown northeast of the gabbro outcrop.

The large masses of greenstone are massive, medium to fine-grained, dark green rocks with segregation-like masses of lighter colored (more feldspathic) material. The intrusive character of these greenstones is well shown at *D* (Fig. 1). However, both greenstone and graywacke are so greatly sheared that the contact relations are obscured by the flowage of the rocks under deformational forces.

[3] Howe, Ernest: Petrographical Notes on the Sudbury Nickel Deposits. ECON. GEOL., vol. 9, pp. 505–22 (esp. 508), 1914.

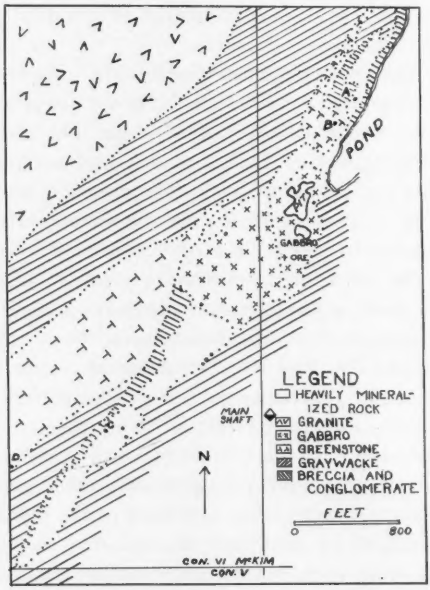
[4] Dickson, C. W.: The Ore Deposits of Sudbury, Ontario. Trans. Am. Inst. Min. Eng., vol. 34, p. 48, 1903.

[5] Tolman, C. F. Jr., and Rogers, A. F.: A Study of the Magmatic Sulfid Ores, p. 30. Stanford University, 1916.

[6] Walker, T. L.: Geological and Petrographical Studies of the Sudbury Nickel District (Canada). Quart. Jour. Geol. Soc., London, vol. 53, pp. 59–60, 1897.

[7] Knight, C. W.: Rept. Royal Ont. Nickel Comm., p. 200, 1917.

The massive greenstones are composed mainly of hornblende, quartz, plagioclase (andesine-labradorite), and biotite, with some magnetite and small amounts of chlorite, zoisite, and apatite. Near the ore body some sulphides are also present. The horn-



GEOLOGICAL MAP OF FROOD MINE AFTER A.P. COLEMAN

FIG. 1. Geological map of Frood Mine. After A. P. Coleman.

blende is blue-green and very ragged, containing many blebs of quartz and some of zoisite and chlorite.

The norite is a medium-grained, dark gray rock composed mainly of plagioclase (labradorite, near andesine) and hypersthene in about equal proportions. In addition, quartz, biotite, and hornblende are present. The hornblende is usually regarded

as secondary after hypersthene. Colony [8] believes it to be due to deuteric processes.

The granite is a medium-grained, pink, mica granite, composed of quartz, orthoclase (or microcline), and biotite, with minor, and probably secondary, muscovite, zoisite, and chlorite. The rock varies from place to place in color and proportion of minerals. The pink phase is cut by irregular dikes of a dark, biotite-rich phase containing fragments of the pink phase. The granite intrudes the norite at the Murray mine two miles to the west and it intrudes the Sudbury series near the west side of the area of the map. Quartz veins are numerous near the granite-graywacke contact, some of them originating in the granite and extending into the graywacke, others cutting the granite. Some of the veins are offset along fractures, indicating movement in the rocks after the injection of the veins. At *B* on the map, a porphyritic granite dike, associated with quartz veins, intrudes the greenstone and graywacke conglomerate. Both the granite and the quartz veins at this locality carry chalcopyrite, suggesting that some of the chalcopyrite of the Frood ore may possibly have been derived from a similar source, which is of course distinct from the norite.

In the paragraph outlining the sequence of events in the area, no mention was made of the gabbro mass that outcrops north of the main shaft. This rock is a quartz-bearing olivine gabbro and is much fresher than the greenstones. The writer believes that it was emplaced about the same time as the norite and granite. In most places it is altered to a varying extent, and in some places, notably around the large open pit near the northeastern end of the mass, it is intimately mixed with sulphide-bearing rock that closely resembles "pyrrhotite-norite." The fresh gabbro is composed of labradorite, augite, olivine, quartz, orthoclase, magnetite, and biotite. Uralitic hornblende is associated with the augite and is believed by the writer to be secondary. Where altered, the gabbro consists of more or less completely uralitized augite, or blue-green hornblende, with biotite, quartz, and andesine, accompanied by varying amounts of magnetite and pyrrhotite.

[8] Colony, R. J.: The Final Consolidation Phenomena in the Crystallization of Igneous Rock. Jour. Geol., vol. 31, pp. 169–178, 1923.

THE ORE.

In most places the ore has no sharp boundary against the country rocks. As mentioned above, there is a complete gradation from graywacke to gossan in some places. In the conglomeratic phases of the graywacke the matrix was more susceptible to impregnation by sulphides than the cobbles of greenstone, lava, and quartzite. The greenstone itself is for the most part not mineralized. The gabbro is mixed with ore-bearing rock in a manner suggesting an igneous breccia. This is very well shown in the railway cut northwest of the main shaft, between the open pit and the pond. Some of the gabbro fragments have sharp boundaries against the sulphide-rich rock, in places marked by fractures carrying a little chalcopyrite, but many of the fragments have gradational boundaries. The fragments may be (1) breccia blocks intruded by an ore-bearing magma, or (2) residual fragments of gabbro that were relatively little altered in a recrystallization of the rock accompanying mineralization.

FIG. 2. Mineralized graywacke. Quartz metacrysts with biotite, hornblende, and plagioclase. X-nicols, × 22.

FIG. 3. Mineralized gabbro. Sulphides (black) in quartz, feldspar, hornblende, biotite. The larger areas of sulphides show mutual boundaries against the non-metallics but a few small sulphide veinlets cut the latter. Ordinary light, × 25.

FIG. 4. Lean ore. Chalcopyrite, pyrrhotite, pentlandite, and non-metallics (black). The same relations between metallics and non-metallics are shown here as in Fig. 3. Almost all the material in the veinlets is chalcopyrite. × 40.

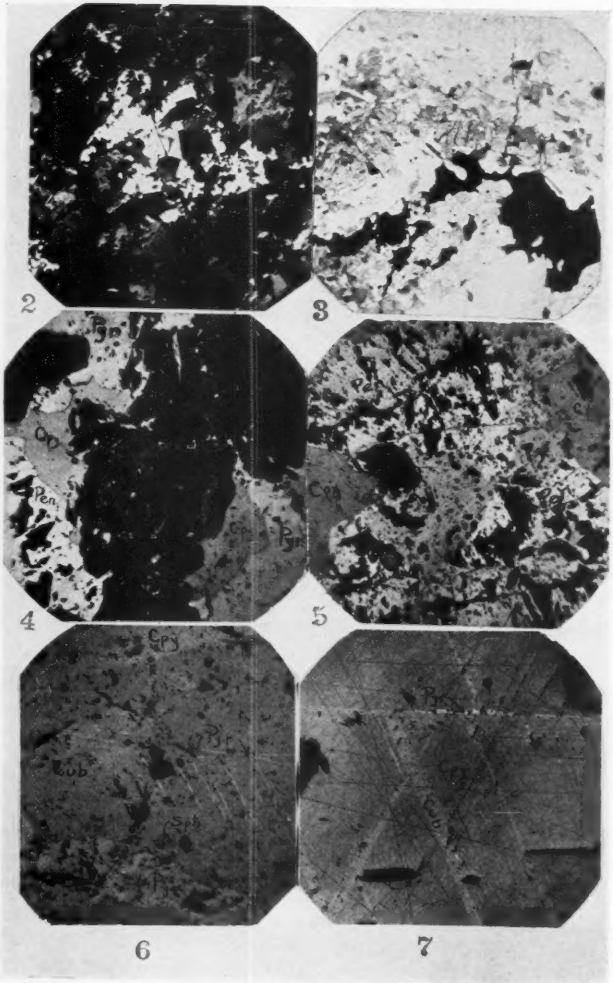
FIG. 5. Chalcopyrite, pentlandite, and pyrrhotite. The boundaries between minerals are smooth but irregular. × 40.

FIG. 6. Cubanite, pyrrhotite, chalcopyrite, and sphalerite. The cubanite contains one veinlet and several small bars of pyrrhotite. The picture was taken at the boundary of cubanite and chalcopyrite, which shows near the top. There is a small mass of sphalerite. × 40.

FIG. 7. Chalcopyrite with cubanite bars oriented in three directions, and one bar of pyrrhotite. × 40.

Figs. 2 and 3 are photomicrographs of thin sections; Figs. 4–7, of polished surfaces.

Cpy = Chalcopyrite; Pyr = Pyrrhotite; Pen = Pentlandite; Cub = Cubanite; Sph = Sphalerite.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The sulphide-rich rock is a distinct rock type and is the same no matter what other rock (graywacke, greenstone, gabbro) is associated with it. It is a dark gray, millimeter-grained, equigranular rock with irregular masses of sulphides up to half an inch across (Figs. 3, 8, and 9). The sulphides vary in amount from a few scattered flakes to practically pure masses with only a few per cent. of non-metallics. The chief non-metallic minerals are hornblende, quartz, biotite, and andesine, with accessory apatite. The relative amounts of the first three constituents named vary from place to place, but on the average, hornblende is roughly equal in amount to biotite and the two together equal the amount of quartz. Andesine forms only a few per cent., and apatite is an accessory, although in places it is quite a prominent one.

The hornblende is a blue-green variety and is mainly in elongate crystals and granular masses, although in small part it takes a fibrous habit. Most of the crystals are ragged in outline and are deeply embayed and spotted by quartz and sulphides. Minute hornblende crystals are scattered throughout the larger areas of quartz. Some crystals, however, mostly occurring near large sulphide masses, have smooth boundaries and no inclusions.

The biotite is deep brown in color and resembles the hornblende in habit as described above. It differs slightly in having a large number of zoisite inclusions but very few quartz inclusions.

The andesine is in small idiomorphic crystals in the larger quartz masses. The grains, although small, are clean and fresh appearing, and do not seem to be altered or crushed.

The quartz occurs as interlocking grains and some large masses that are several times as large as any of the other constituents (Fig. 2). These large masses contain small crystals, particularly of feldspar and hornblende, that are not in any regular orientation and give no indication of being remnants of larger individuals. The andesine crystals especially are clear and entirely free from evidences of strain or crushing.

The metallic minerals are in irregular masses that show mutual boundaries against non-metallics (Figs. 8 and 9). Biotite, horn-

blende, and quartz commonly show their own crystal outlines against metallics. In a few places, however, the metallics cut the non-metallics in smooth walled veinlets (Figs. 3 and 4). These

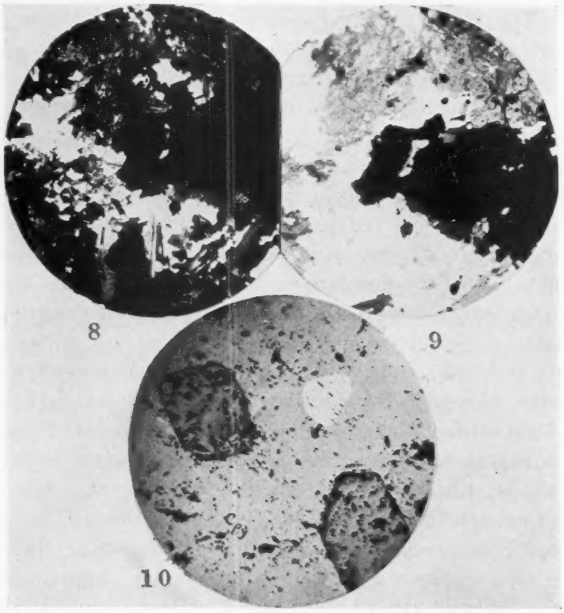


FIG. 8. Same as Fig. 9. X-nicols, × 20.

FIG. 9. Mineralized greenstone. Sulphides (black) in non-metallics, showing mutual boundaries. Ordinary light, × 25.

FIG. 10. Chalcopyrite with two magnetite crystals and a mass of galena (white). Cubanite bars are present but are very faint in the photograph. × 40.

Figs. 8 and 9 are photomicrographs of thin sections; Fig. 10, of polished surface.

veinlets are minor in amount, and the conclusion is inevitable that metallics and non-metallics crystallized at the same time. This statement applies to mineralized graywacke as well as mineralized gabbro and greenstone.

The evidence for complete recrystallization of the country rock during mineralization is as follows:

(1) The fact of contemporaneity of silicates and sulphides, even in sedimentary rock—the graywacke.

(2) The general resemblance of all types of heavily mineralized rock no matter what rock types they are associated with.

(3) The presence of the large metacrystals of quartz.

(4) The xenomorphic granular texture of most of the mineralized rock.

There is almost a total absence of evidence for replacement, for the mutual relations of the minerals point to contemporaneity. Therefore, there was not a series of replacements of the wall rock, but rather a comparatively sudden reorganization and recrystallization of the non-metallic part of the ore along with the mineralization. This process was magmatic rather than hydrothermal.

Mineralography of the Ore.—Specimens of rich ore from between the 2000 and 2800 foot levels were studied in addition to those obtained from outcrops. The ore is massive but somewhat gneissic in texture, some of the specimens showing the constituent minerals as rude bands and others being sheared. The main metallic minerals are chalcopyrite, cubanite, pyrrhotite, and pentlandite. They are present, within wide limits, in all the specimens. One specimen a little over three inches long is made up almost entirely of chalcopyrite. Another about equal in size is nearly all pyrrhotite. Pentlandite occurs in masses up to one and one-quarter inches and in vein-like lenses about an eighth of an inch wide.

Pyrrhotite and pentlandite here are similar in appearance to that from other places, but the chalcopyrite shows two unusual characteristics. It is distinctly paler in color than that usually seen and it shows sphenoidal parting similar to that described and figured by Schwartz.[9] Cubanite occurs in laths along these planes (Fig. 7) and also in masses associated with, and at times

[9] Schwartz, G. M.: Primary Relationships and Unusual Chalcopyrite from Copper Deposits of Parry Sound, Ontario. ECON. GEOL., vol. 19, pp. 209–213, 1924.

completely surrounding, the pale chalcopyrite. Its boundaries (transitional?) against chalcopyrite are faint, but are sharply defined against pentlandite.

Besides the four sulphides, there are numerous octahedra of magnetite, usually about one millimeter in size, although one was seen that was four millimeters across. Non-metallics occur in varying amounts but are practically absent in the richer ore.

The following minerals, listed in order of abundance, were identified in polished specimens: chalcopyrite, cubanite, pyrrhotite, pentlandite, magnetite, sphalerite, galena, mineral X.

In rich ore, chalcopyrite is the most abundant mineral and shows veinlets of pyrrhotite and pentlandite in it. These veinlets are irregular in width but have smooth outlines and are quite commonly discontinuous elongate masses with a marked linear distribution (Fig. 5). The contacts are those of idiomorphic crystal masses and do not seem to be those characteristic of replacement. In some instances pyrrhotite crystals extend out into chalcopyrite in a manner suggestive of crystallization against chalcopyrite crystals. In other cases, small, smooth, sharp-pointed pyrrhotite veinlets cut chalcopyrite. In nearby situations conditions just the reverse may be found, where chalcopyrite seems definitely to be later than the pyrrhotite and to have crystallized against it. The most probable explanation for such relations is contemporaneity. Similar relationships are shown between chalcopyrite and pentlandite, between pyrrhotite and pentlandite, and between pyrrhotite and cubanite (Fig. 6), indicating essential contemporaneity of crystallization of all four sulphides. Boundaries between cubanite and chalcopyrite are rarely sharp. Parallel bars of cubanite ingrown in chalcopyrite are common. On following these bars back into the cubanite mass the amount of chalcopyrite becomes less and less, until only minute ragged patches are observed with the highest magnification. Even these patches disappear farther in from the large areas of chalcopyrite.

In addition to the chalcopyrite-cubanite intergrowths, there are similar intergrowths of pyrrhotite and cubanite (Fig. 6). The pyrrhotite bars are on the whole more minute than those of cu-

banite in chalcopyrite, but they are needle-like and occur in sets of parallel rods that strongly suggest unmixing in the solid state. The presence of these intergrowths is additional evidence of contemporaneity of formation of the minerals concerned.

Chalcopyrite and pentlandite continued forming longer than pyrrhotite and cubanite, as is shown by the presence of tiny veinlets cutting the non-metallics (Figs. 3 and 4). The amount of sulphides in the veinlets is, however, very minor. Pentlandite, sphalerite, and an undetermined mineral, here referred to as mineral X, are associated with chalcopyrite in these veinlets and seem to have continued forming as long as the chalcopyrite.

Magnetite occurs sparingly in specimens with small amounts of sulphides, but is conspicuous in the rich ore. It occurs mainly as euhedral crystals, rarely as irregular elongate masses. The crystals are found in all four of the main sulphides and in the non-metallics, commonly with only a slight rounding of the angles. In a few instances, magnetite crystals are embayed by the sulphides. The magnetite in the irregular masses is minor in amount and it is contemporaneous with part of the sulphides since the relationships are similar to those of the pyrrhotite and pentlandite in chalcopyrite described above.

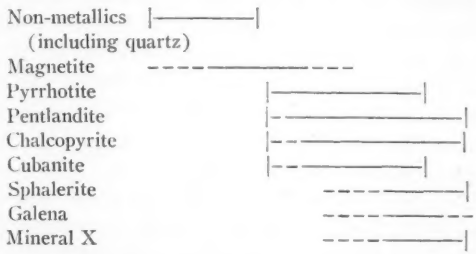
Sphalerite occurs in irregular, minute masses associated with all the other sulphides, but mainly with chalcopyrite, much of it being around magnetite crystals in chalcopyrite. It occurs as small irregular masses similar to those of pyrrhotite, etc. described above. Ine one instance a small irregular mass cuts squarely across a bar of cubanite in an intergrowth. The writer regards the sphalerite as contemporaneous with the other sulphides, although he thinks, because of its small amount, that it started to crystallize later. Sphalerite also occurs as smooth veinlets in non-metallics, as noted above.

Galena occurs as small, rounded masses with smooth outlines. The amount is less than that of sphalerite, and the masses also have a more regular outline than sphalerite.

Small amounts of a white, anisotropic, metallic mineral are

also present in masses too small for determination by microchemical tests. The color is whiter than that of galena. The mineral is distinctly anisotropic, the colors being a brownish or pinkish cream and a dirty white, and it shows multiple twinning. The hardness is about the same as galena. The mineral resembles stibnite, but it is improbable that stibnite would occur under these conditions and the writer prefers to refer to it as mineral X.

The paragenesis of the ore is shown by the diagram below.



The ore body was formed by the recrystallization of a brecciated zone of rock at a very high temperature. The sulphides of the ore body were brought in essentially simultaneously, not in a well defined sequence. The non-metallic minerals developed during the mineralization were hornblende, biotite, quartz, and andesine plagioclase. Replacement was practically absent and the conclusion is that the mineralization was a peculiar type of magmatic action. The evidence for recrystallization of the country rock during mineralization is strong and precludes the hypothesis of crystallization from a molten mass.

GENERAL CONCLUSIONS.

1. The Frood ore is not in norite but in reorganized graywacke, gabbro, and greenstone.

2. The rocks were altered by the ore-depositing agencies, which caused the formation of hornblende, biotite, quartz, and andesine.

3. The four main ore minerals—chalcopyrite, cubanite, pyrrhotite, and pentlandite—were formed essentially simultaneously.

4. The ore body is a magmatic deposit, but it is not wholly the result of crystallization from a melt.

The writer wishes to express his appreciation for advice and criticism received in the course of this study from Professors Edson S. Bastin and Albert Johannsen.

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BERYLLIUM MINERALS IN BRAZIL.[1]

LUCIANO J. MORAES.

THE recent developments in metallurgical research which have resulted in the production of certain beryllium alloys, especially those of beryllium and copper, possessing qualities of outstanding promise in industry, may add additional interest to the following brief notes on the occurrence of beryllium minerals in Brazil.

These notes are based in part or mainly on my own observations during various excursions and in part on published reports of the Brazilian Geological and Mineralogical Survey, as well as on personal communications of different colleagues of that survey, especially Drs. Djalma Guimarães, Moraes Rego, and Horace E. Williams. I am indebted to Mario Pinto (for the notes of the Glycerio occurrence), and also to Dr. O. R. Albuquerque, professor of mineralogy at the Ouro Preto School of Mines.

Beryls are commonly found in pegmatite dikes and are recovered in some of the mica, asbestos, and tourmaline mines, as a by-product. They also occur in quartz veins in granitic and gneissic rocks, as well as in veins in mica-schists. In places large crystals weighing several tons are encountered during mining operations; unfortunately for the miner, these large crystals are commonly full of flaws and so possess no great value as gem material.

Although the best known occurrences and most productive deposits of beryl minerals in Brazil are found in the contiguous regions of southern Bahia and eastern Minas Geraes, the mineral is also found in many other regions of this country where, as yet, it has not been explored or studied to any considerable extent. The better known Bahia-Minas region extends eastwards from the eastern margin of the old sedimentary rocks forming the main

[1] Published by permission of the Director of the Brazilian Geological and Mineral Survey.

ridge of the Serra de Espinhaço (Backbone Ridge), to within 50 or 60 miles of the coast, forming a belt over 100 miles wide and reaching from 13° 30′ to below 22° of south latitude, a distance of over 600 miles.

This region is characterized by granites, gneisses, and mica-schists of the crystalline complex with, here and there, considerable infaulted areas of the older sediments; on the high divides in the north between the main streams, superposed on the crystalline rocks, is a series of soft horizontal sediments forming wide plateaus of late geological age—perhaps late Tertiary.

In the state of Minas Geraes, beryl and aquamarine are also found at the following places farther south and west: Brejahuba, Esmeralda, S. Anna dos Ferros, Antonio Dias, S. Domingos da Prata, Taquarana, Espera Feliz, Bicas, etc. But perhaps the most interesting and commercially important deposits in the state are those which occur near Sant. Anna da Onça, situated about half way between the cities of Peçanha and Figueira. Figueira is situated on the railway at the great elbow of the Rio Doce. At several places in this neighborhood large deposits have been found and are being mined. These mines have yielded some large crystals, one of which measured over 17 feet long by 40 inches across, weighing upwards of three tons. These are in pegmatite dikes which yield both these large masses and smaller crystals which occur in pockets. Most of these stones, small as well as large, have irregular rounded edges and are commonly opaque, with a milky color which results from occluded gaseous matter. However, some of them have a beautiful deep blue color but unfortunately are so full of flaws as to have little or no value as gem material.

From Figueira, the railway follows down the Rio Doce to Victoria, the capital of the state of Espirito Santo. About 30 miles below Figueira, at the tourmaline mines near the station of Lajão, there is a considerable production of beryl and aquamarine, as well as of tourmaline.

Beryl is reported from various points in the environs of the city of Rio de Janeiro; and in the state of this name, from the Rio do Ouro district and from near São Gonçalo, a short distance

from Nictheroy, the capital of the state. But the most important and promising deposit of beryl in this state is found near the town of Glycerio, a recent discovery, where the gems occur in a great pegmatite dike. The working face in the open-cut mine at this place is between 40 and 50 feet across, yielding gems of good color.

In all this region considerable mining has been done at various localities in the past in the search for mica and kaolin, resulting in most cases in the discovery of some one or other of the rarer minerals such as tourmaline, beryl, or columbite.

In southern Bahia, the industry centers about the town of Conquista, which is quite a market for aquamarines. They are generally of too light a color, however, to command the best prices as gem stones. These are mostly from quartz veins in the crystalline rocks of the region. Producing centers in this region of Bahia, are Poções, Verruga, Encruzijada and Condeuba, and much of the material from the valley of the Jequitinhonha river, in northern Minas, finds its way to Conquista. Other reported localities in Bahia are Gandú, Ituassú, Jacobina and Bom Jesus dos Meiras. About ten miles west of the last-mentioned place, an interesting occurrence of emeralds is found in the Serra das Equas, and has been discussed by Professor Just.[2]

In Minas Geraes, the most northerly occurrences of aquamarine and beryl are near the towns of Fortaleza and Salinas, the product of the mines going largely to Conquista. However, since earliest colonial times, diamond washing on the lower Jequitinhonha river yielded a quota of beryls and tourmalines, as well as diamonds and rarely a chrysoberyl. The principal producing centers along this river are São Miguel, São Pedro, Arrassuahy and Minas Novas.

Perhaps the most important market for the semi-precious stones is the city of Theophilo Ottoni, situated in the high mountainous region to the south of the lower Jequitinhonha. This city is connected by rail with the port of Caravellas on the east coast, which is frequented by small coasting steamers from Bahia and Rio de

[2] Just, Evan: Emeralds, at Bom Jesus dos Meiras. Econ. Geol., vol. 21, pp. 808–810, 1926.

Janeiro. The most important producing centers of the beryllium minerals in this region are Marambaia, Rio das Americanas, Pampam and Lufa, all of which places are situated in the highlands to the north of that city. The gems from the Marambaia district are the most highly prized because of their deep blue color. Southeast of Theophilo Ottoni, gems are also reported from the headwaters of the Rio S. Matheus, while to the southwest, important producing centers are the Rio Surubim and Santa Maria de S. Felix. Near this last-mentioned place, are some of the oldest and most productive mica mines in the country, in which considerable amounts of columbite as well as beryl and tourmaline have been found.

Brazilian Geological and Mineralogical Survey,
Rio de Janeiro, Brazil.

DISCUSSION AND COMMUNICATIONS

SECONDARY CONCENTRATION OF LAKE SUPERIOR IRON ORES.

Sir: In my discussion of Dr. J. W. Gruner's article [1] on Secondary Concentration of Lake Superior Iron Ores, published in this Journal in the August number, 1932, page 487, the statement was made that not one igneous rock cutting the iron formation has been identified on the main formation of the old Menominee Range. In making this statement, the writer overlooked the occurrence of a strong dike in the SW.–SE. Section 5, 39–29, in old abandoned mine workings there. This dike is mentioned by Rominger in early publications of the Michigan Geological Survey, and its existence was checked by some old drilling of the Penn Iron Mining Company. This occurrence was known to the writer at the time of writing the discussion but was overlooked, and the writer is indebted to Mr. L. P. Barrett for calling it to his attention.

This remains, as far as the writer can learn, the only occurrence of igneous rock cutting the main, or Middle Huronian, iron formation on the old Menominee Range. There are later intrusives cutting the Upper Huronian Hanbury slate, which, of course, must at some unknown point cut through the Middle Huronian iron formation unless their point of issuance into the Upper Huronian is at some of the localities, known to be extensive, where the Middle Huronian is missing due to removal by the Upper Huronian unconformity.

The fact remains that no relation has been observed between ores of the old Menominee and igneous rocks cutting the iron formations or located near them, and in only the one case above mentioned has a dike been found in contact with the iron formation.

STEPHEN ROYCE.

[1] ECON. GEOL., vol. 27, pp. 189–205.

REVIEWS

The Oil and Gas Resources of New Mexico. By DEAN E. WINCHESTER. Pp. 223, pls. 33, figs. 11. State Bur. Mines and Min. Resources, Bull. 9. Socorro, New Mex., 1933. Price, $1.50.

This bulletin summarizes the results of the search made for petroleum in New Mexico from the first important production in 1909 to January, 1932. It assembles for the first time the scattered literature on the subject, and presents a clear picture of what has already taken place in the search for oil in the State, with data on the undeveloped areas as well as methods for solving some of the problems which have presented themselves during this search.

The report is divided into five parts.

The first portion concerns itself with the stratigraphy of the State. Most of the material has been taken bodily from Darton's work, and the correlation chart is largely from U. S. G. S. sources.

In the second part of the report, Winchester divides the State into five "areas" which are more or less structural and stratigraphic units. For each of these areas, both pools and prospects are considered in order of importance and promise, and for the pools, the location, history, areal and subsurface geology, structure, development, character of the oil, and production methods are discussed amply, and often structure maps and characteristic well logs are included. Undrilled or partially unproven structures are located and described. An especially valuable contribution is the matching together of small areas to give the relation of the pools and structures to the regional structure.

The author holds that important pools still remain undiscovered in the State. In the southeastern part, these pools may be on structures not reflected at the surface, or on known structures at greater depths than have been tested with the drill. In the northeastern area, deeper drilling is warranted in a number of places, and in the northwestern area, it is believed that production can be obtained from structures similar to that of the Rattlesnake pool, if Pennsylvanian sands are reached.

The median area of the State from north to south, and the southwestern part, are not considered favorable for accumulation except very locally.

Carbon dioxide has been found associated with Triassic strata in the northeastern area, and additional discoveries are expected. This gas is used in the manufacture of "dry ice."

The third part of the bulletin is devoted to a description of two occurrences of bituminous sandstone, used to some extent as road metal.

The fifth portion contains a brief description of geophysical methods and equipment.

Among the illustrations are an oil and gas map and a geologic map of the State, and 20 structure maps of known fields and areas of special importance. The oil and gas map shows proven fields, the location of about 200 anticlinal structures, and the location and results obtained by drilling nearly 1,000 wildcat wells. A selected bibliography concludes this truly excellent bulletin.

M. H. BILLINGS.

UNIVERSITY OF ILLINOIS,
URBANA, ILL.

Treatise on Sedimentation. By W. H. TWENHOFEL. Pp. 926, figs. 121, 2d edit. Williams & Wilkins, Baltimore, 1932. Price, $8.00.

This second edition of a worthy predecessor is a complete revision. The old matter has been drastically changed, new material added, and the illustrations doubled in number. A valuable book before, it is much more valuable now.

The chapter headings, which indicate its content, are: I, Sources and Production of Sediments; II, Transportation, Deposition, Diagenesis, and Lithification; III, Conditions Modifying Sedimentary Processes; IV, Sediments and Organisms; V, Products of Sedimentation; VI, Structures, Textures, and Colors; VII, Realms of Sedimentation; VIII, Field and Laboratory Studies. Chapters V and VII are particularly outstanding.

This book is a necessity to students of stratigraphy, sedimentary petrology, general geology, and petroleum geology.

ALAN BATEMAN.

The Book of Metals. By DONALD WILHELM. Pp. 341. Harper & Bros., 1932. Price, $4.00.

This is a fascinating story of metals and alloys, simply and delightfully told. Under the headings for each metal, for example, tin, nickel, or gold, the author tells of the ancient history, development of the ores, and modern procedure of obtaining and preparing the metals. The characteristics and behaviorism of each metal are given. One learns about early history, the story of pewter, or why platinum is sought.

It is not, and is not meant to be, a technical book. It originated in stories to the author's boys. Yet the technical man will enjoy it as much as the layman. The style is clear and pleasing. One is not bored by

statistics but he learns that "it takes just about as much gold as you could shovel into a bathtub to make a million dollars." Or, "aluminum wasn't found, like items made of brass, bronze, or copper, in good King Tut's tomb!" His analogies are breezy and pithy, his information correct, and it is a treat to read the book.

Origin and Environment of Source Sediments of Petroleum. By P. D. TRASK. Pp. 323, figs. 39, tables. Published for American Petroleum Institute, by Gulf Publishing Co., Houston, Texas, 1932.

This valuable work sums up the painstaking investigations, carried on by Dr. Trask for five years, of the source of petroleum, a project of the Research Program of the American Petroleum Institute.

The chapter headings, which show the contents, are as follows: Collection and Preparation of Samples; Measurement of Organic Content; Distillation Tests; Texture of Sediments; $CaCo_3$ Content; Organic Matter and Environment; Detailed Analyses of Organic Constituents; Change in Organic Content with Depth; Comparison of Past and Recent Sediments; Miscellaneous Results; Theoretical Considerations. There is a summary and a 60-page appendix of tables.

The book covers a new field in geology and is a valuable contribution to stratigraphy and to the theories of petroleum geology. Everyone interested in petroleum geology should read it.

A Descriptive Petrography of the Igneous Rocks. Vol. II, The Quartz-Bearing Rocks. By ALBERT JOHANNSEN. Pp. 428, figs. 119. University of Chicago Press, Chicago, 1932. Price, $5.50.

This volume is the companion of Volume I, which was reviewed in this JOURNAL in the May number, 1932, and it will be followed by succeeding volumes. It contains detailed systematic descriptions of the extremely numerous quartz-bearing rocks arranged according to Johannsen's classification. Most of the descriptions are accompanied by chemical analyses and excellent illustrations, and a pleasant touch is the inclusion of photographs of the various geologists whose names are associated with the particular rocks described. The rock descriptions are detailed and thorough, but the average user may not enthuse regarding the classification employed or the complication instead of simplification of vocabulary. For example, the term "quartz-leuco-kaligranite" hardly strikes one sympathetically, and it is with regret that the user finds that the nice old familiar term of graphic granite, which conveyed at once a mental picture of the rock, has been changed to runite. The book should, however, prove to be a valuable reference volume to every petrologist.

BOOKS RECEIVED.

By DAVID GALLAGHER.

Die Bodenschätze Deutschlands. Band I. By E. KRENKEL. Pp. 301, figs. 71. Gebrüder Borntraeger, Berlin, 1932. Price, 22.50 RM; bound, 24.50 RM.

Wesen und Wege der Paläontologie. By E. HENNIG. Pp. 512, figs. 198. Gebrüder Borntraeger, Berlin, 1932. Price, 28 RM; bound, 30 RM.

Die schweizerische Eisenerzeugung, ihre Geschichte und wirtschaftliche Bedeutung. By H. FEHLMANN. Pp. 255, figs. 76. Beiträge zur Geologie der Scheiz, Geotechnische Serie, Lief. XIII, B. 3. Hans Huber, Bern, 1932.

The Mineral Industry during 1931: Vol. XL. By G. A. ROUSH. Pp. 735. McGraw-Hill, New York, 1932.

Oil Prospecting in Kentucky by Resistivity Methods. By J. H. SWARTZ. Pp. 23, figs. 16. U. S. Bur. Mines, Tech. Paper 521. Washington, 1932.

A Magnetic Study of Some Iron Deposits. By E. F. STRATTON AND J. W. JOYCE. Pp. 32, figs. 20. U. S. Bur. Mines, Tech. Paper 528. Washington, 1932.

Mineral Production of the World, 1924–1929. By L. M. JONES. Pp. 103. Mineral Resources of the U. S., 1930, Part I. U. S. Bur. Mines, Washington, 1932. Price, 10 cts. A statistical summary by countries.

Research Council of Alberta, Twelfth Annual Report, 1931. Pp. 53. Report No. 27, Edmonton, 1932.

Geology of the Antelope Gold Belt. By A. E. PHAUP. Pp. 119, pls. 6, tables 13. Southern Rhodesia Geol. Survey, Bull. 21. Salisbury, 1932. General geology, petrology, and economic geology; gold with pyrrhotite and pyrite in actinolite-schist after serpentine between masses of granite.

Geology of the Country Around Que Que, Gwelo District (So. Rhodesia). By A. M. MACGREGOR. Pp. 113, pls. 14, tables 5. Southern Rhodesia Geol. Surv. Bull. 20. Salisbury, 1932. General geology, stratigraphy, petrology, and economic geology of a 750 square mile area containing important gold deposits. Price, 2/6.

Uganda Protectorate, Annual Report of the Geological Survey, 1931. Pp. 20. Entebbe, 1932. Record of organization and activities.

Carbonizing Properties and Constitution of Various Coals from Ala., Pa., W. Va. and Ill. By A. C. FIELDNER et al. U. S. Bur. Mines, Tech. Papers 519, 524, 525, 531 and 542, Washington, 1932. Five papers herein listed together.

Alpine Zone of Mt. Washington Range. By E. ANTEVS. Pp. 118, figs. 38. Merrill and Webber Co., Auburn, Maine, 1932. An interesting discussion of glaciation, and a valuable contribution on frost action in these mountains; also chapters on the vegetation.

Mining Petroleum by Underground Methods. By G. S. RICE. Pp. 159, figs. 38. U. S. Bur. Mines, Bull. 351. Washington, 1932. Price, 15 cts.

Index of Analyses of Natural Waters in the United States, 1926 to 1931. By W. D. COLLINS AND C. S. HOWARD. U. S. Geol. Surv. W. S. P. 659–C. Washington, 1932. Price, 5 cts.

Ground Water in North-Central Tennessee. By A. M. PIPER. Pp. 238, pls. 9, figs. 7. U. S. Geol. Surv. W. S. P. 640. Washington, 1932. Price, 35 cts. Geologic and stratigraphic summary, relationship and distribution of ground water.

Geology and Ground-Water Resources of the Dalles Region, Oregon. By A. M. PIPER. Pp. 189, pls. 9, figs. 3. U. S. Geol. Surv. W. S. P. 659–B. Washington, 1932. Price, 25 cts.

Thermal Springs of Virginia. By F. REEVES. Pp. 56, pls. 8, figs. 4, tables 7. Virginia Geol. Surv. Bull. 36. University, Va. 1932. Geology, chemistry, source of heat and water.

The Lower York-James Peninsula. By J. K. ROBERTS. Pp. 58, pls. 21, figs. 7, tables 7. Virginia Geol. Surv. Bull. 37. University, Va., 1932. Cretaceous and Tertiary geology, mineral resources, and geologic history.

Building Stones of the Union of South Africa. By W. WYBERGH. Pp. 244, figs. 3, pls. 2. Union of South Africa Geol. Surv. Mem. 29. Pretoria, 1932. Distribution, character, weathering, testing, and choice of building stones.

Geology of the Country Surrounding Vryheid. By W. A. HUMPHREY AND L. J. KRIGE. Pp. 66, figs. 2. An explanation of Sheet No. 102 (Vryheid). Union of South Africa Geol. Survey, Pretoria, 1932.

Kimberlite and Associated Occurrences of the Iramba Plateau. By E. O. TEALE. Pp. 10, sketch map. Tanganyika Geol. Surv. Short Paper No. 10. Dar es Salaam, 1932.

Tanganyika Geological Survey, Annual Report, 1931. By E. O. TEALE. Pp. 49, sketch map. Tanganyika Geol. Survey, Dar es Salaam, 1932. Activities and progress, with brief summaries of attainments.

Lithium. Pp. 27. Imperial Institute, London, 1932. Price 6d. Sources, preparation, uses, production and marketing, world occurrence by countries, bibliography.

General Report of the Geological Survey of India, 1931. By L. L. FERMOR. Pp. 150. Rudistae from Eastern Persia. By O. Kühn. Pp. 28. Records of the Geol. Surv. of India, Vol. LXVI, part I. Calcutta, 1932.

The recently published 20-volume index (336 pages) of ECONOMIC GEOLOGY for 1905 to 1925, compiled by J. M. Nickles, may be obtained for $3.00 from W. S. Bayley, University of Illinois, Urbana, Ill.

SCIENTIFIC NOTES AND NEWS

Sidney Paige has been appointed mineral advisor to the Sultan of Turkey.

Frederic G. Clapp has sailed for Teheran, Persia, for a stay of several months as advisor to the Government on oil production.

R. J. Parker, of the Rhodesian Selection Trust and assistant manager of the Roan Antelope mine, is visiting the Kenya region and the Roan Antelope property in Northern Rhodesia, and later will return to London.

Ralph Arnold, of Los Angeles, has formed a corporation known as the Arnold Exploration Company, to mine gold in Eldorado County, Calif.

Stewart Campbell, well known as State Inspector of Mines for Idaho since 1920, has opened an office at 104 Bannock St., Boise, Idaho, and will resume the practice of mining and consulting engineering.

A. L. du Toit, of Johannesburg, South Africa, has been awarded the Murchison medal and an award from the Murchison Fund, by the Geological Society of Great Britain.

D. H. McLaughlin, of Harvard University, has been appointed secretary of the Society of Economic Geologists to succeed Edward Sampson, whose resignation will take effect at the conclusion of the annual meeting of the Society to be held at Princeton, New Jersey, July 7–8.

A. Beeby Thompson, of London, has gone to Bagdad in the interests of the British Oil Development Co., Ltd.

George H. Garrey has almost completely recovered from his serious accident of last summer, and will soon return to his home in the East.

Donald F. MacDonald, formerly with the U. S. Geological Survey, is now teaching geology at St. Francis Xavier University, Antigonish, Nova Scotia.

H. E. McKinstry, after spending some time in geological work at the Hollinger mine, has sailed for the Transvaal for a visit of several months.

The Geological Society of Chicago on March 9 was addressed by Nevin M. Fenneman, of the University of Cincinnati, on the subject "Cyclic and Non-Cyclic Erosion."

S. H. Knight, professor of geology of the University of Wyoming, has been appointed state geologist, with headquarters at Laramie. The office at Cheyenne has been discontinued by an act of the State Legislature.

The papers for the forthcoming Lindgren Memorial Volume are now completed and ready for the printer.

A World Petroleum Congress is to be held at the Imperial College of Science and Technology, South Kensington, London, on July 20–25. The geological section of the program includes papers on modern developments in exploration, significance of regional distribution of oilfields, and geological aspects of their development. A dinner to foreign delegates is set for Thursday evening, July 20. For particulars, write to the Secretary, World Petroleum Congress, Aldine House, Bedford Street, London W. C. 2.

Friedrich Rinne, Professor Emeritus of Mineralogy at the University of Leipzig and Honorary Professor of the University of Freiburg, died at Freiburg in Br. on March 12.

J. Leslie Urquhart, director of the New Guinea Goldfields and chairman of Russo-Asiatic Consolidated Mining and Mount Isa Mines, died of pneumonia in London on March 13, aged 58.

EMMONS MEMORIAL FELLOWSHIP.

The Emmons Memorial Fellowship in Economic Geology is available for this year (stipened $1200). Applicants should be qualified by training and experience to investigate some problem in economic geology and should submit a definite statement of their problem to the Committee, under whose oversight the work will be undertaken at any institution approved by them. The Fellow must give his entire time to the problem, which may be used for a doctorate dissertation. Applications and accompanying testimonials should be submitted not later than May 15. Application blanks and further information may be obtained from Alan M. Bateman, Charles P. Berkey, Waldemar Lindgren, or the Secretary, Columbia University.

Copies of books mentioned under "Reviews" or under our "New Book List" (see advertisement page) may be purchased through our Journal Bookshop by writing to W. S. Bayley, University of Illinois, Urbana, Ill.

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